3D audio sound scenes panorama and technological horizons

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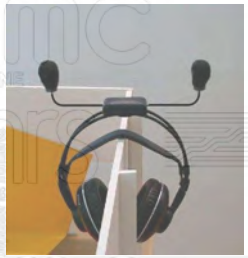
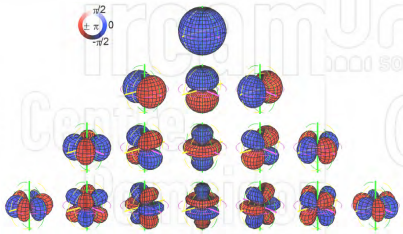
Research Domains

3D Reproduction techniques





Spatialisation/reverberation tools

ircam Tools

FLUX

Auditory Spatial cognition

KMB - july-Sept 2003 - 4500 visitors

SPACE / AUDITION

Space
System of laws governing the juxtaposition of objects (figures, magnitude, distances) and allowing perception.

Geometry
Medium devised by abstraction from perception allowing to explain observed phenomena.

Qualitative/Quantitative repres.
Topology, metric

Physics
Propagation medium for acoustic waves

Thinking
Support for abstraction, reasoning, memory

Importance of space for audition
- audio stream segregation (e.g. cocktail party effect)
- identification of sources (localised or diffuse)
- identification of sources transformation by propagation medium (room effect)

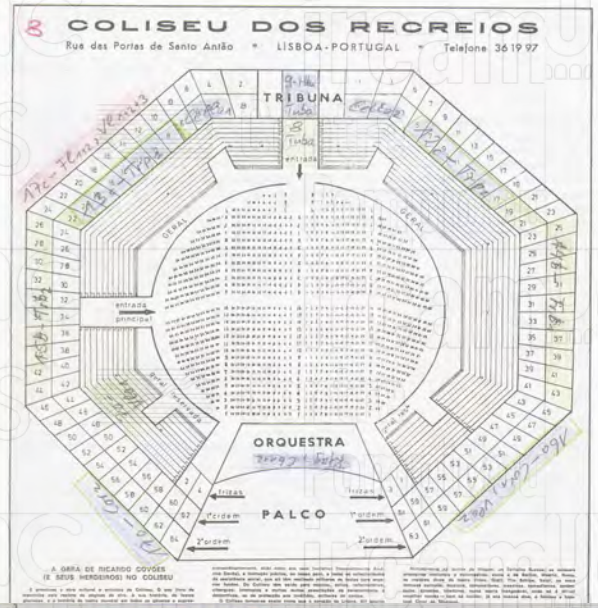
Importance of audition for represention of space
- audition is a major sensory modality for space representation
- omnidirectionnal and distal
- Direction and distance

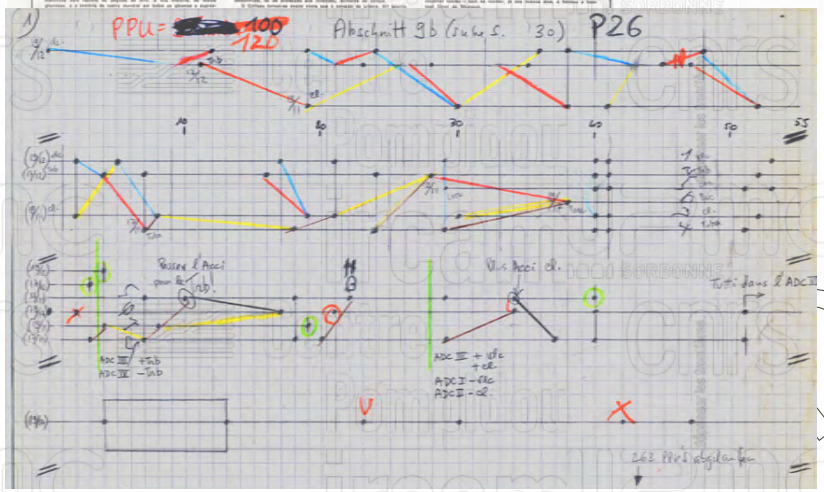
(vision is restricted to limited solid angle, touch is limited to a finite horizon)

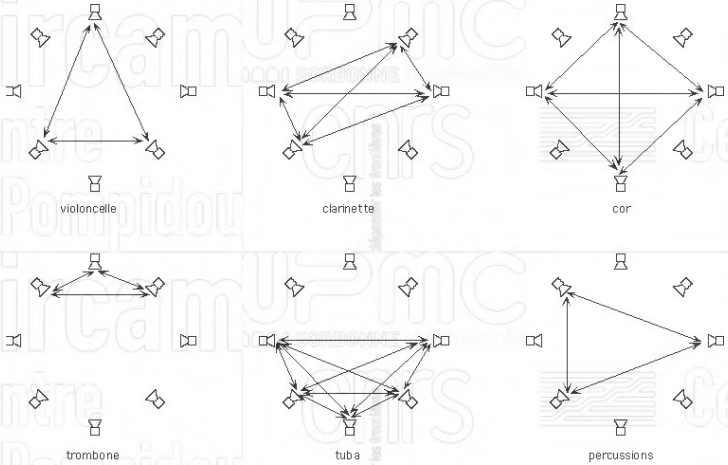
Luciano Berio - *Coro (1976)*

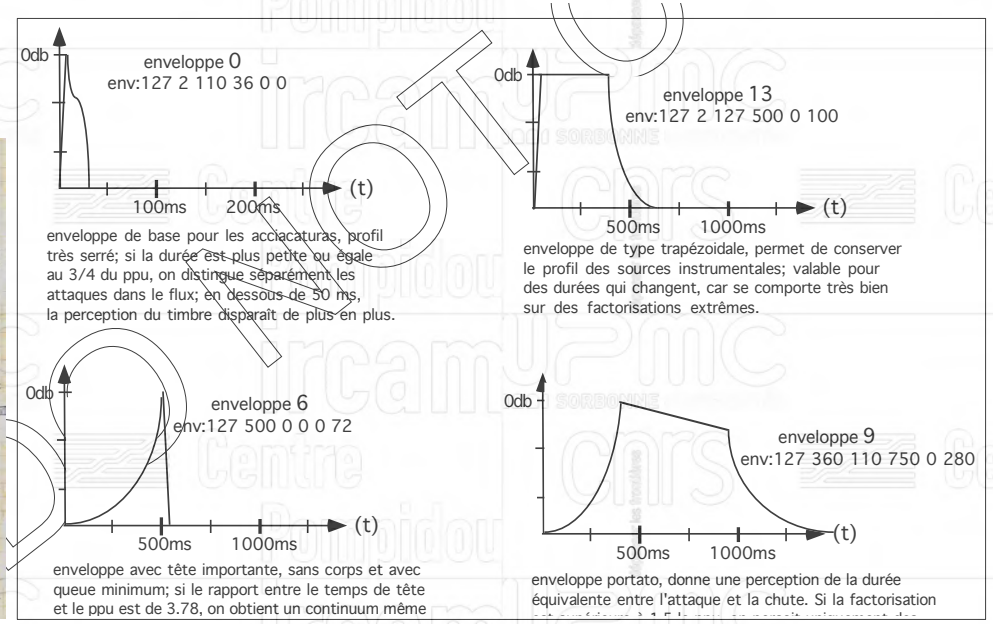
posizione degli strumenti e delle voci

Emmanuel Nunes - *LICHTUNG I - LICHTUNG II*

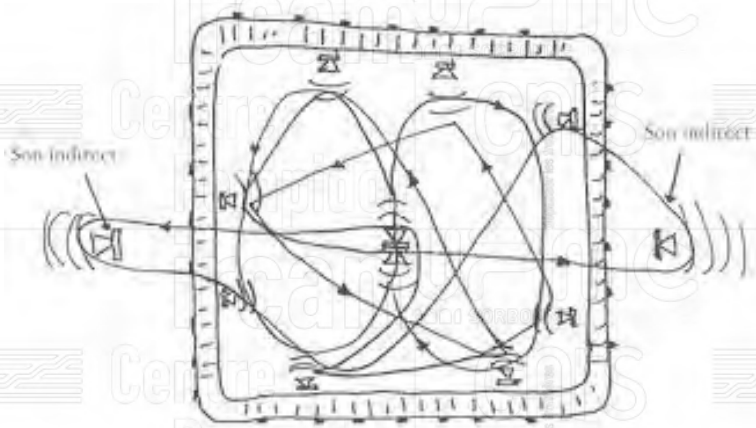


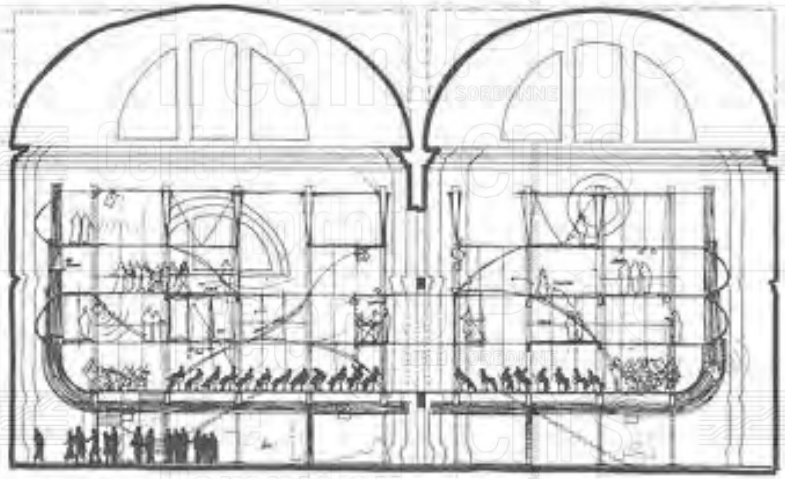


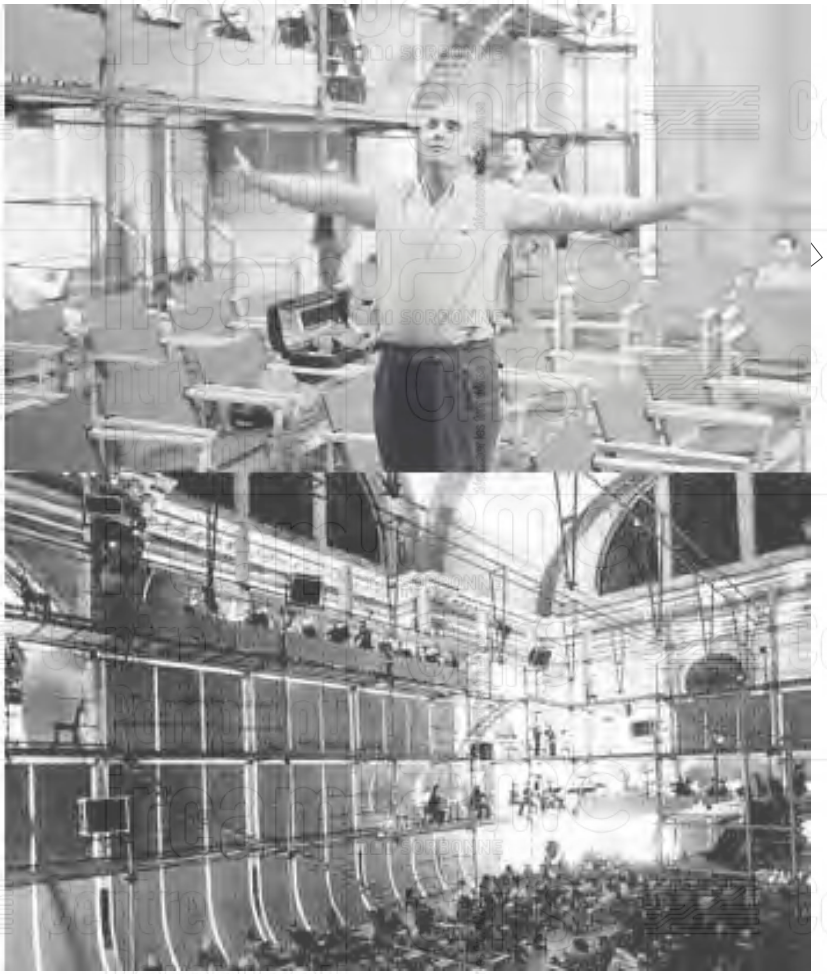




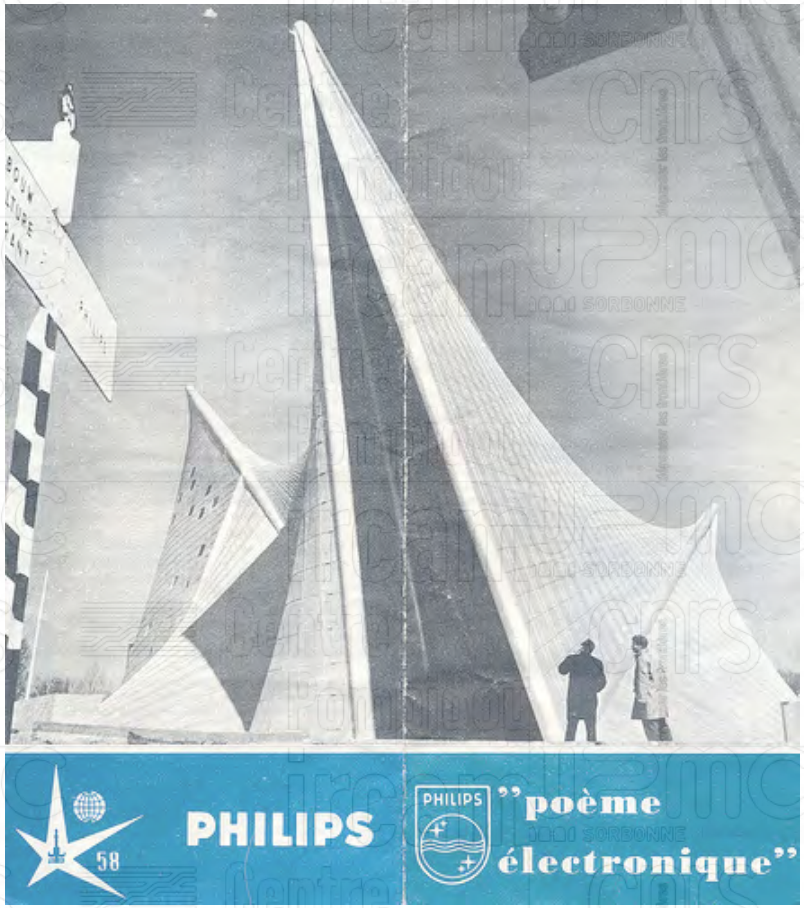
Luigi Nono - *Prometeo (1984)*

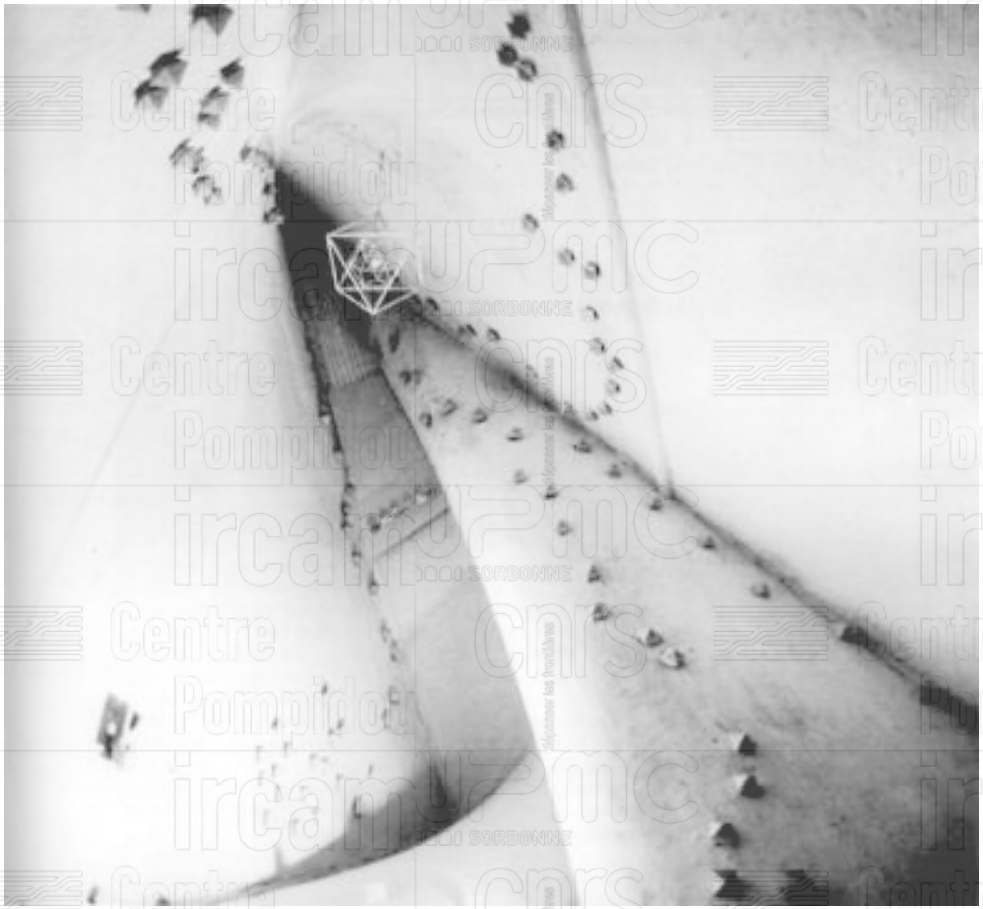






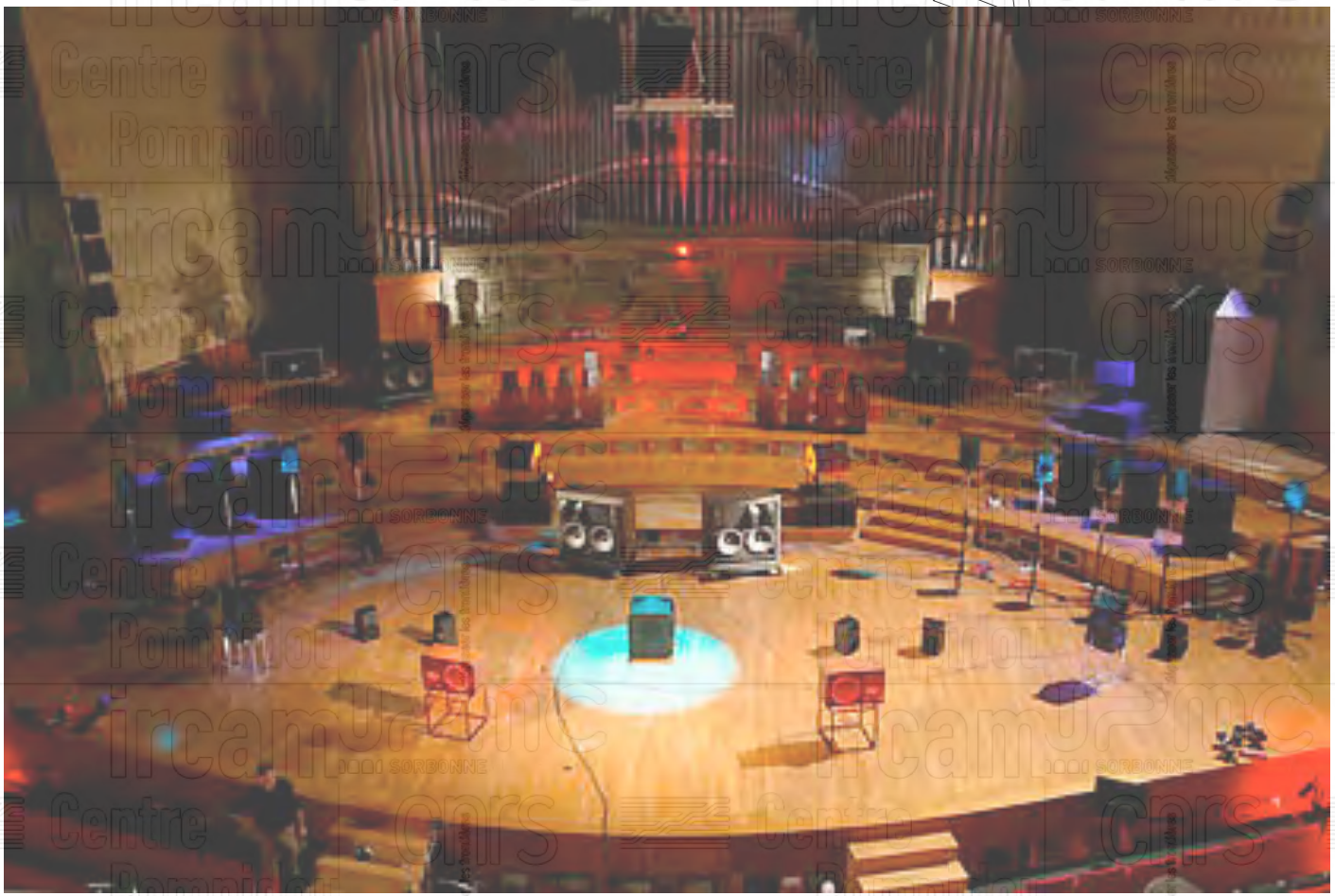
Varese - Xenakis - Le Corbusier - *Poème électronique*





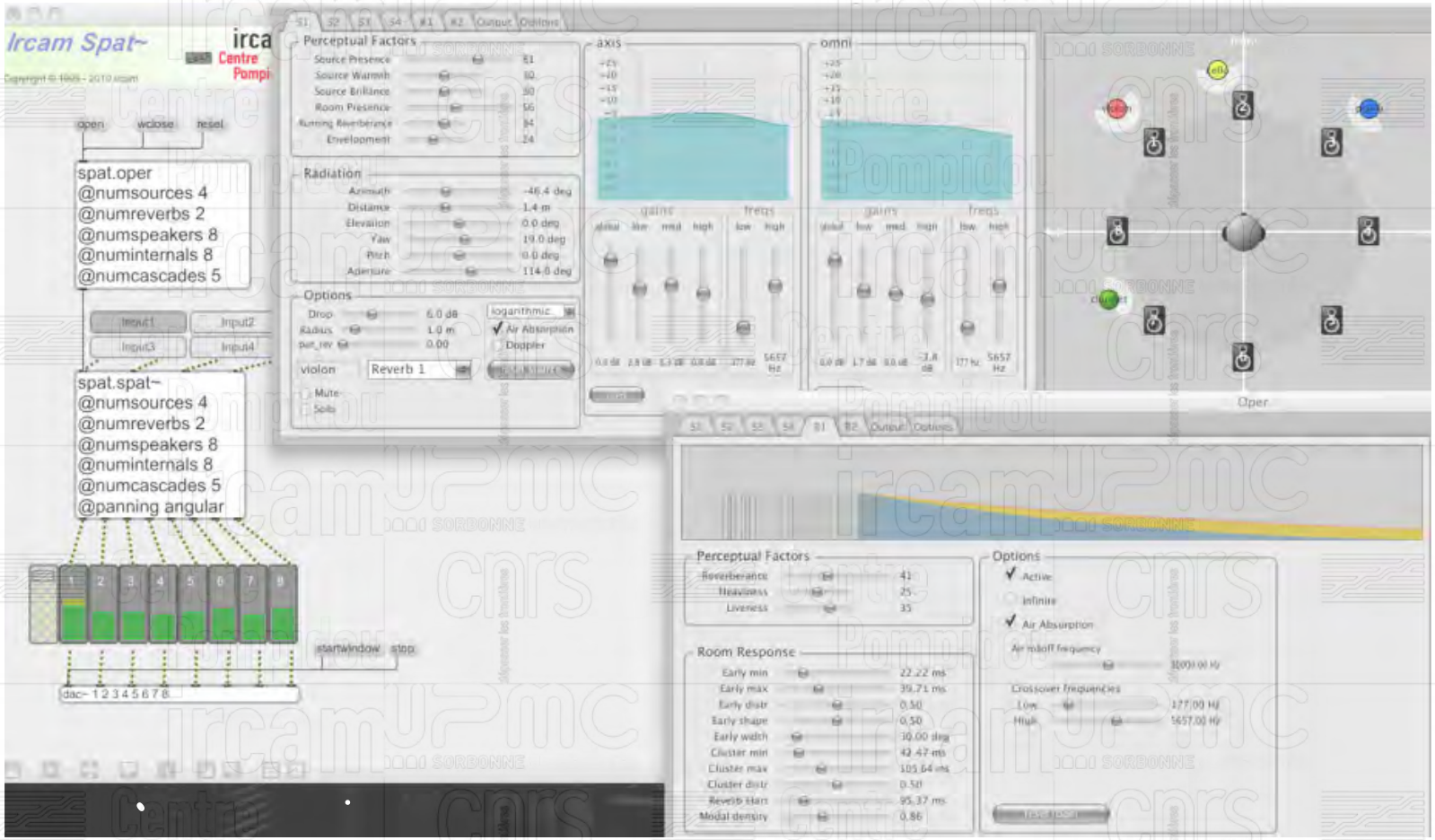
Pavillon Osaka -

Acousmonium GRM



Karlheinz Stockhausen - *Kontakte(1960)*

Real time control / synthesis of spatialization



SOFTWARE DEVELOPMENT

IRCAM Spat~

- C++ libraries with API (e.g. ircam-Tools plug-in suite)

ircam Tools

FLUX:: sound and picture development

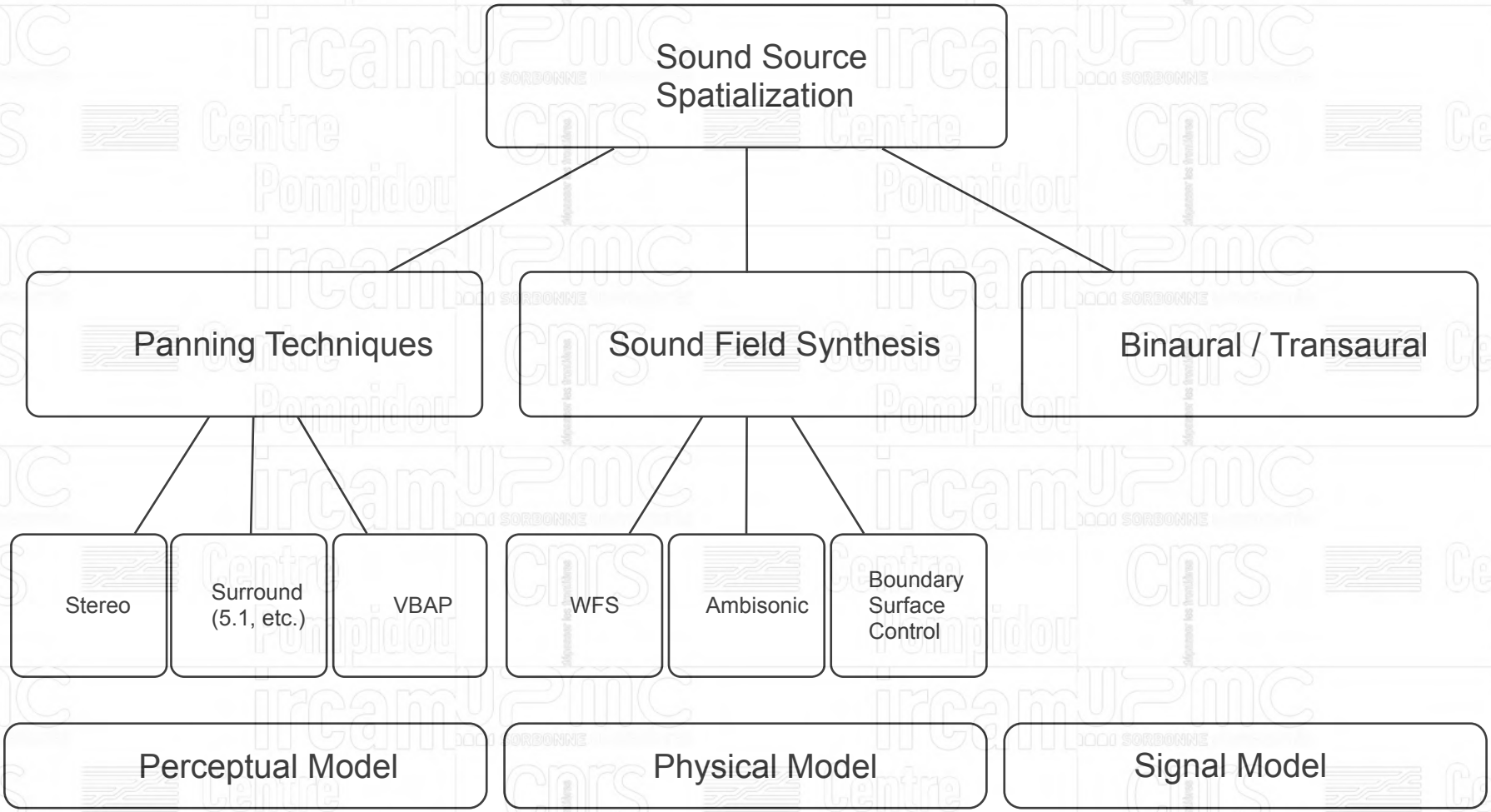
Sound spatialisation models and technologies

Stakes : Recording / Reproduction / Synthesis

Models	Associated technologies
Scene description Encoding/Decoding Transformation	Miking techniques Loudspeaker setup Panoramic laws

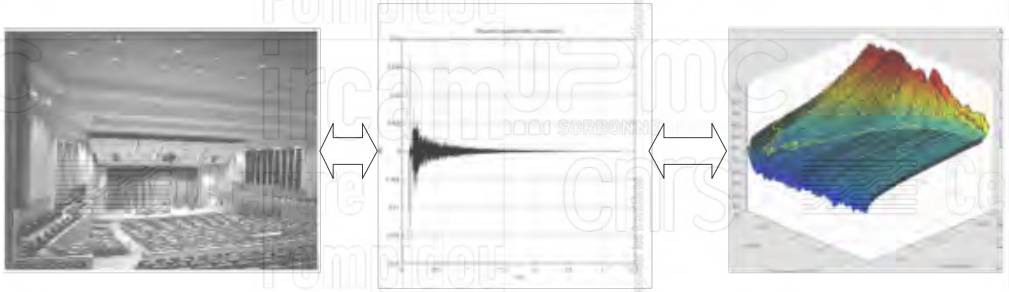
- Signal (sampling) -> binaural
- Physical models -> HOA, WFS,…
- Perceptual models -> stereo and extensions

Sound spatialisation techniques



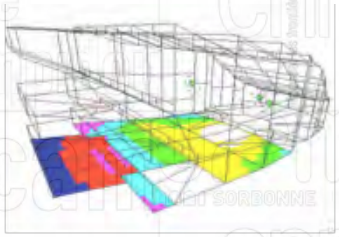
Representation model of Room Effect

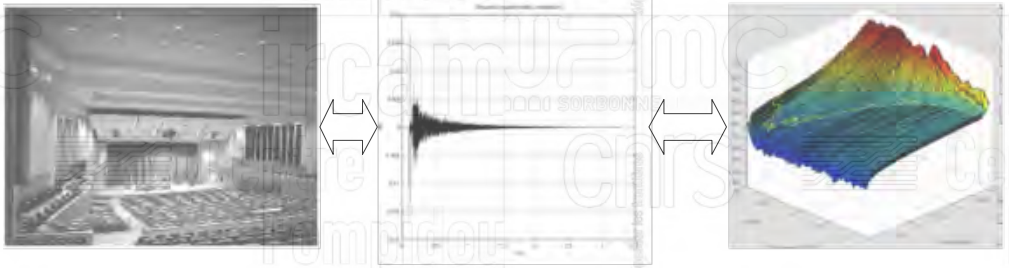
Signal representation



Representation model of Room Effect

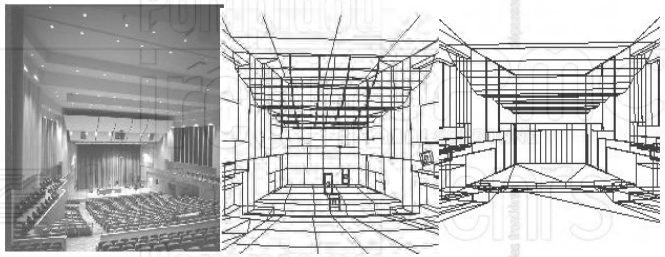
Architectural representation ⟺ Signal representation

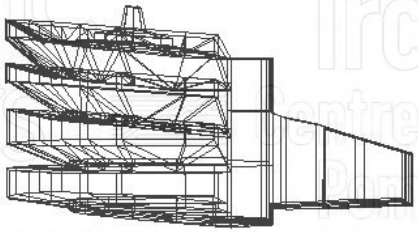


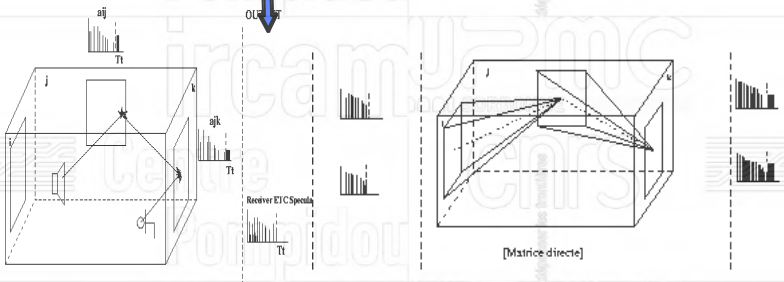


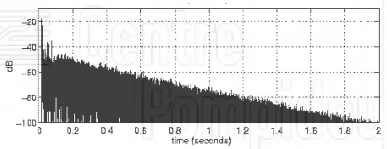
Acoustical modeling

***Physical** approach*:
Acoustics synthesis derived from geometrical room description
- VR reality approach



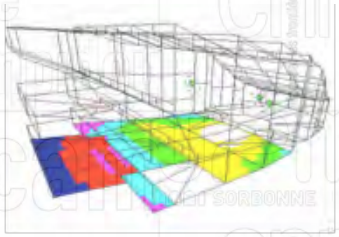


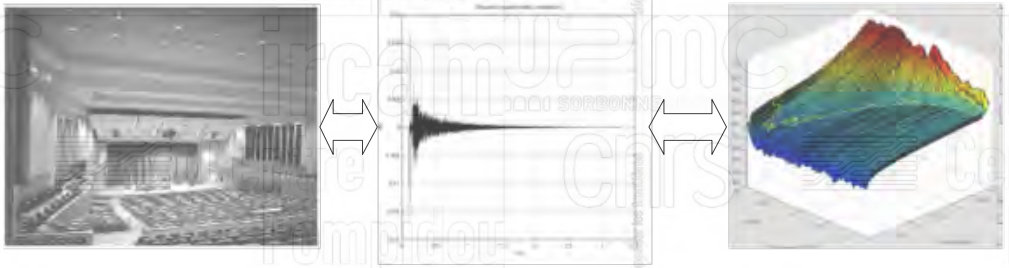




Representation model of Room Effect

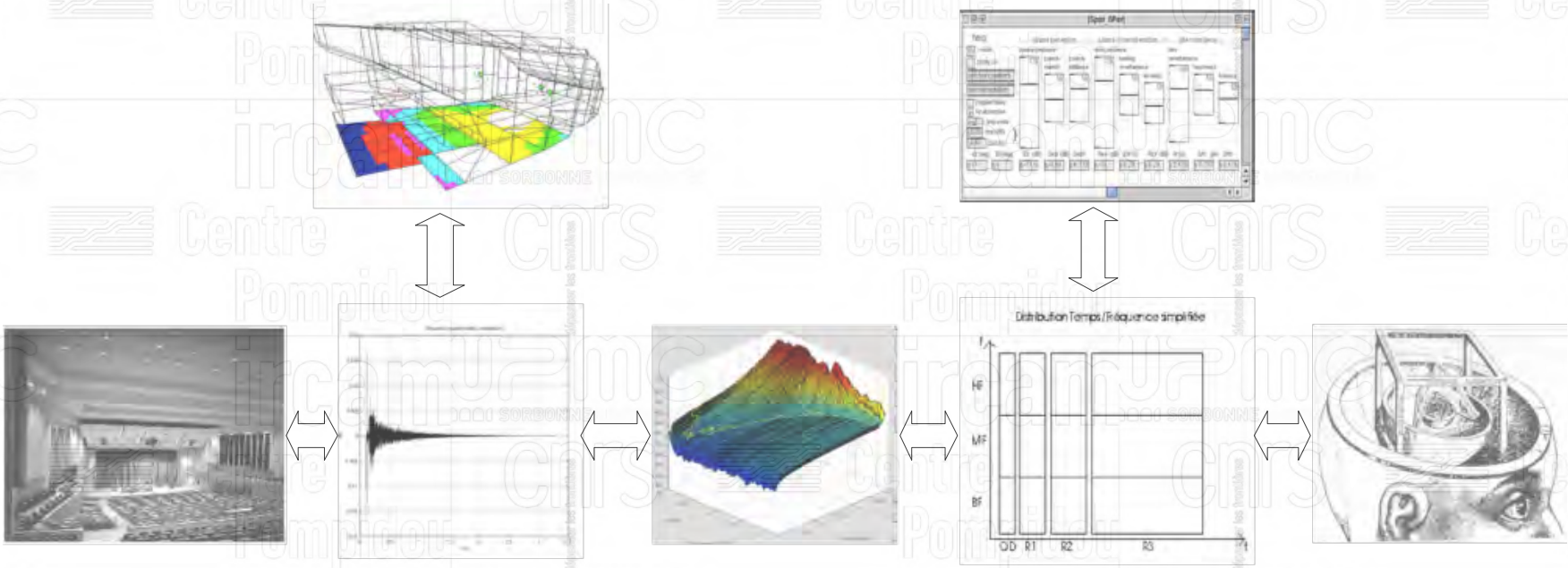
Architectural representation ⟺ Signal representation





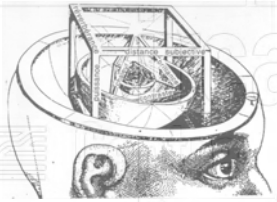
Representation model of Room Effect

Architectural representation ⟺ Signal representation ⟺ Perceptual representation

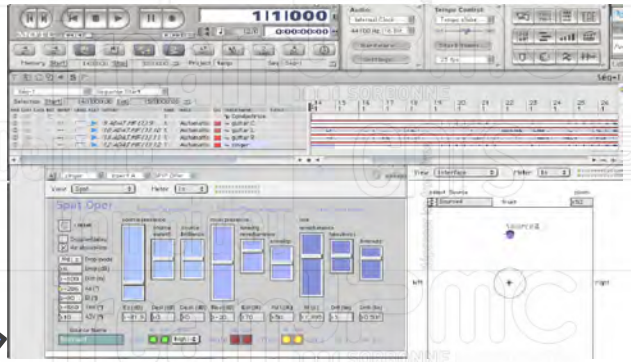


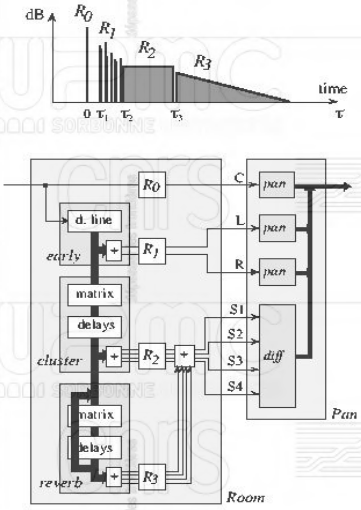
Perceptual model of Room Effect

***Perceptual** approach*:
Acoustics synthesis derived from psychoacoustic studies
- musical approach



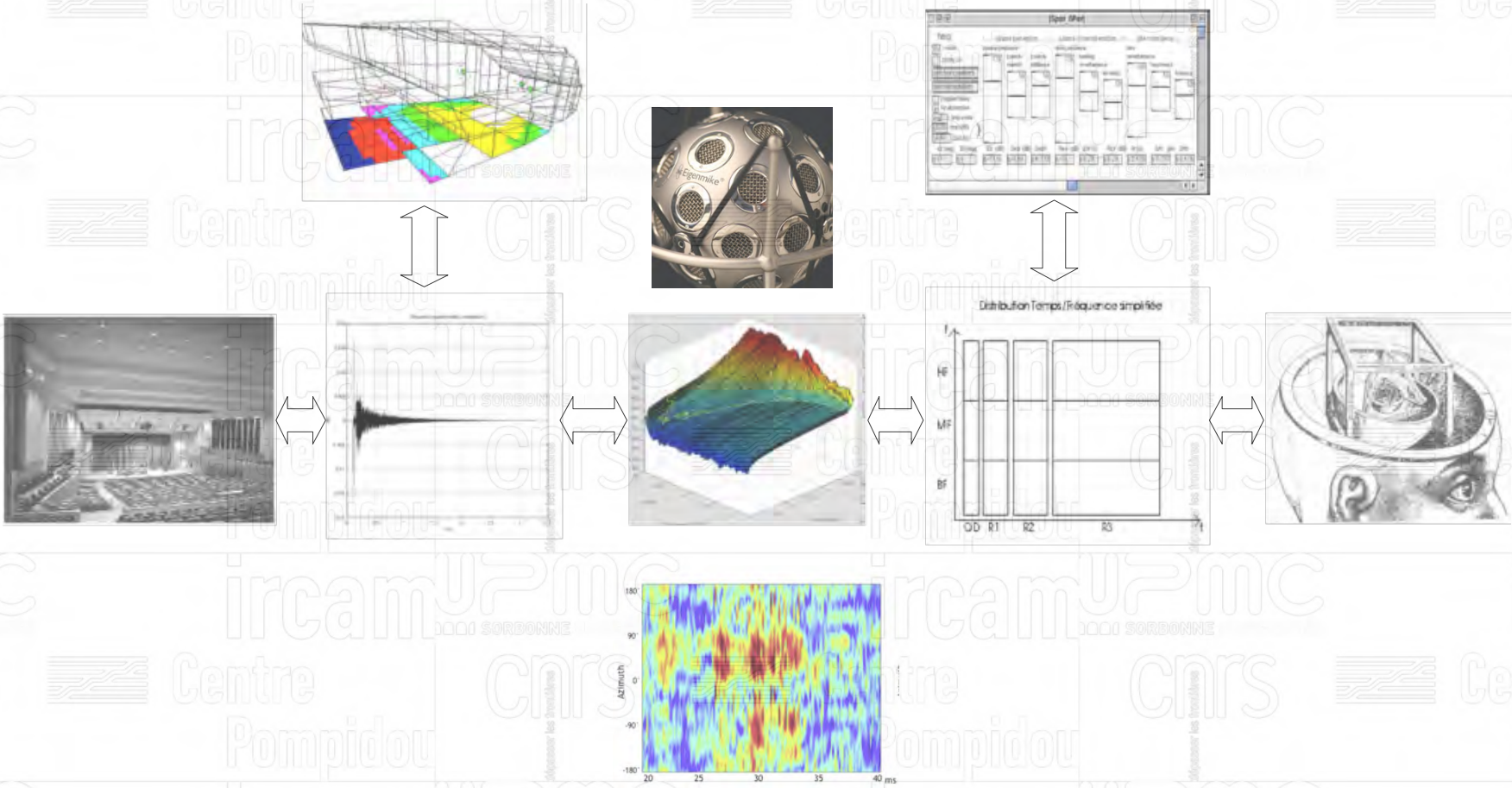
***Perceptual** approach*:
Acoustic parameters derived from the properties of a room impulse response, room acoustics / tonmeister knowledge and practice.





Representation model of Room Effect

Architectural representation ⟺ Signal representation ⟺ Perceptual representation



PRESENTATION OVERVIEW

1 - Synthesis of sound source location and radiation

- WFS
- HOA
- Radiation synthesis

2 - SoundField analysis

- Soundscape recording / transformation with SMAs
- Directional Room Impulse response with SMAs and SLAs
- Application to hybrid reverberation

3 - 3D Binaural Broadcast

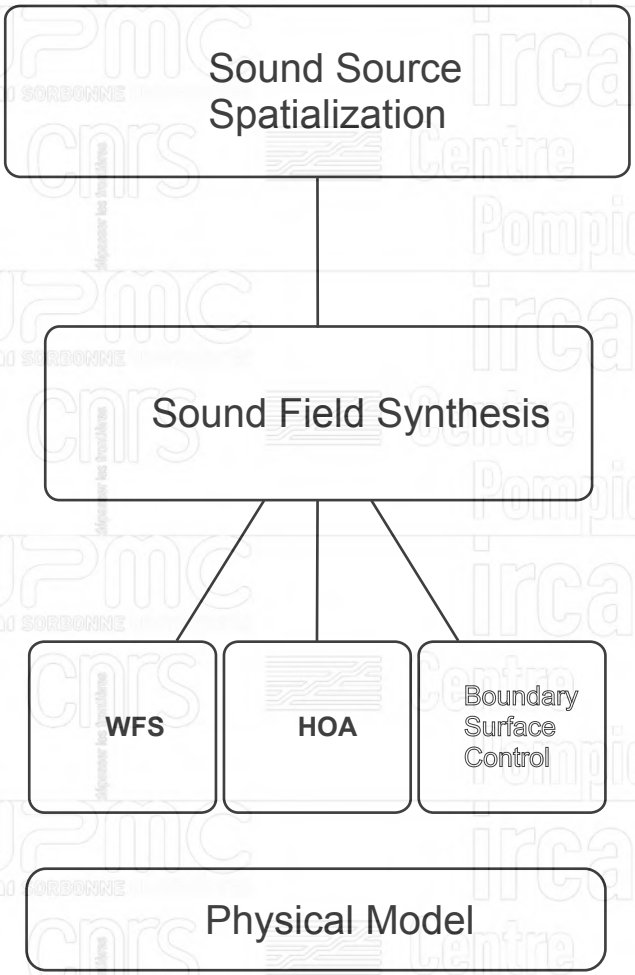
4 - Auditory spatial cognition

5 - Distributed sound spatialization

1 - Synthesis of sound source location and radiation

- WFS
- HOA
- Radiation synthesis

Sound Spatialization Techniques

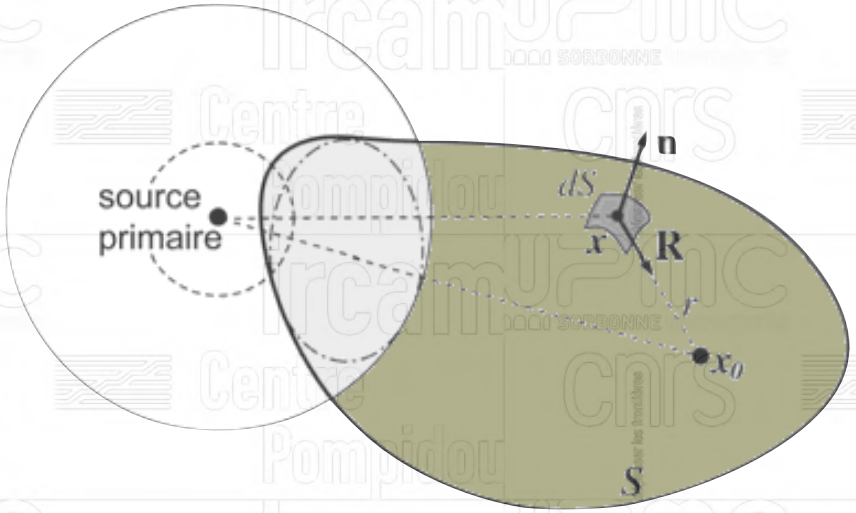


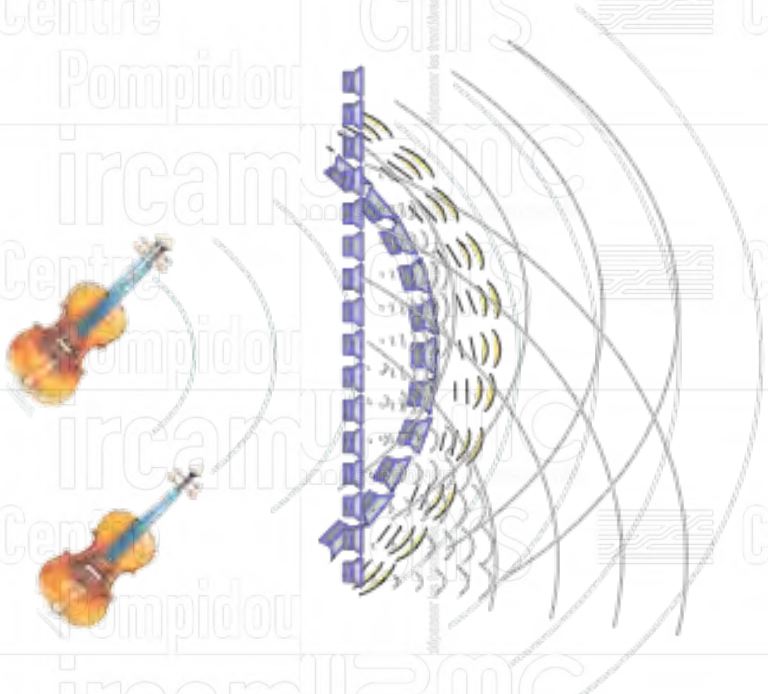
1 - Synthesis of sound source location and radiation

- WFS
- HOA
- Radiation synthesis

Wave Field Synthesis

$$P(x_0, f) = \int\int_S [\nabla P_0(\vec{x}, f)\vec{n} - \vec{R}\vec{n}(1 + jkr)P_0(x, f)/r]\frac{e^{-jkr}}{4\Pi r}dS$$

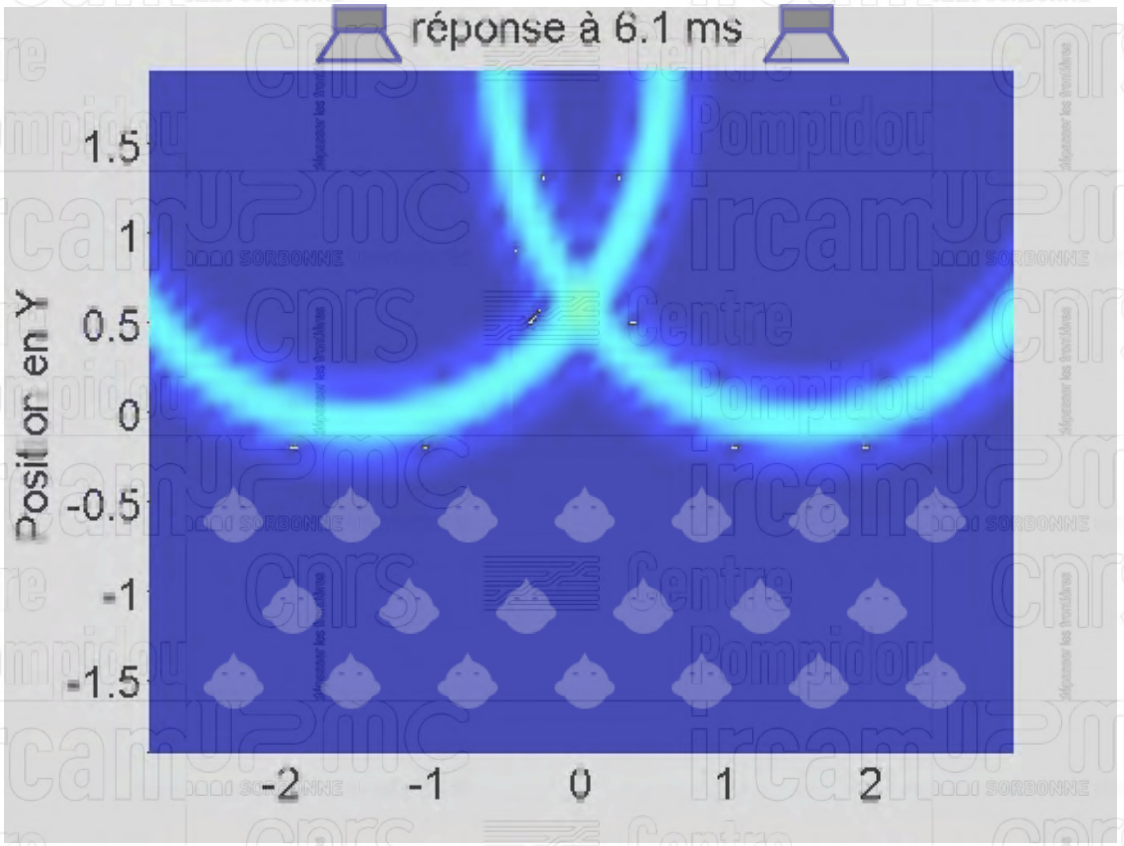




A.J. Berkhout, D. de Vries - Univ. Delft (1988)
R. Nicol - Univ. Le Mans (1999)
E. Corteel - UPMC (2004)
P-A Gauthier - Univ. Sherbrooke (2007)
N. Epain - Univ. Marseille (2007)

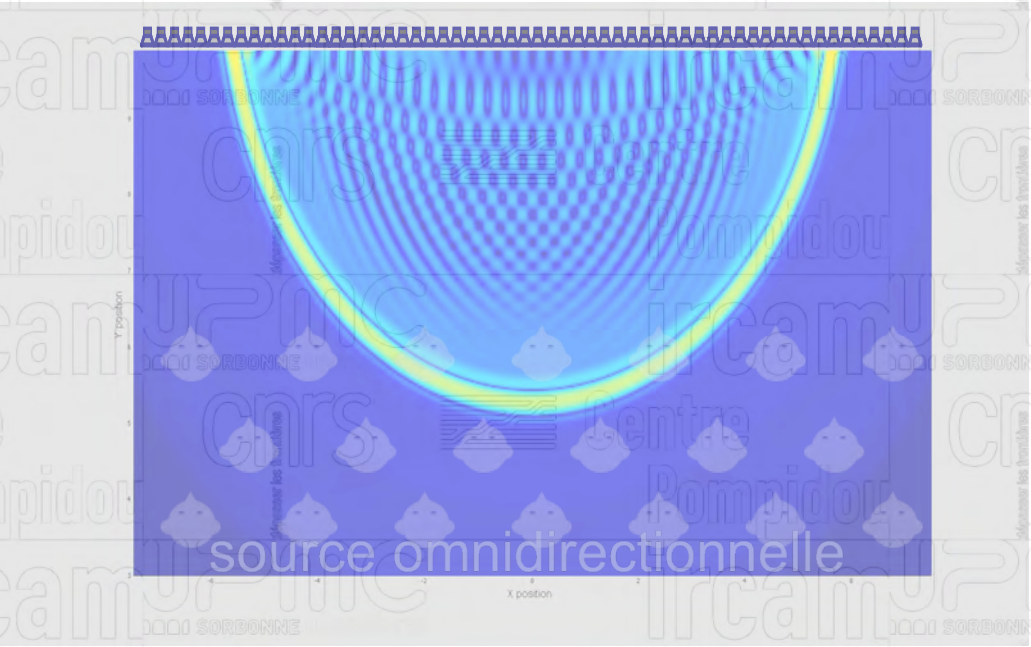
Stereo

simulation of a source in the median plane



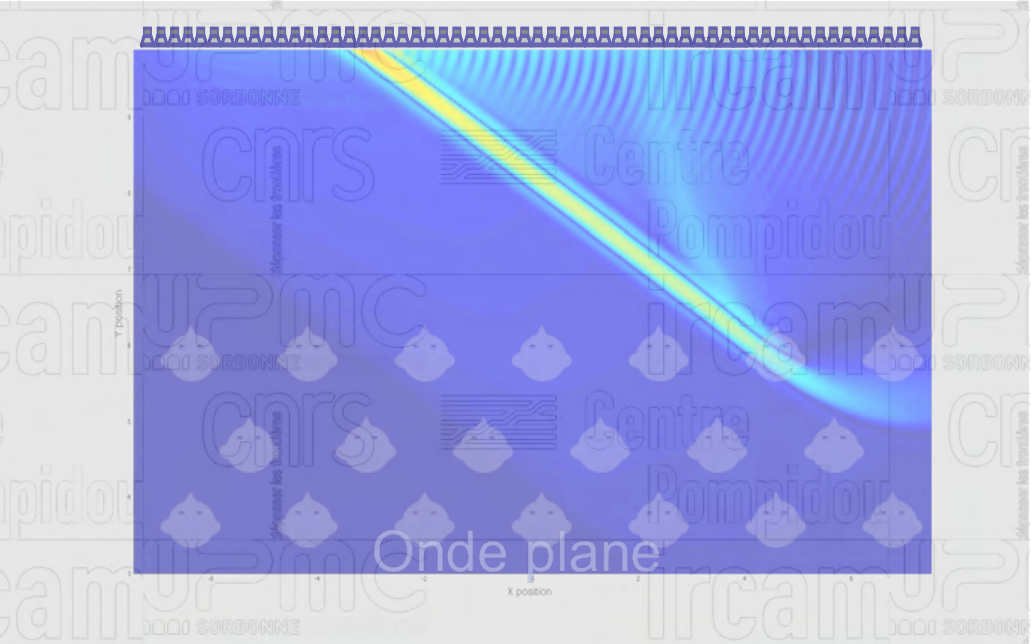
Loudspeaker array systems -WFS

simulation of a source located behind the loudspeaker array [x=0; y= 12]



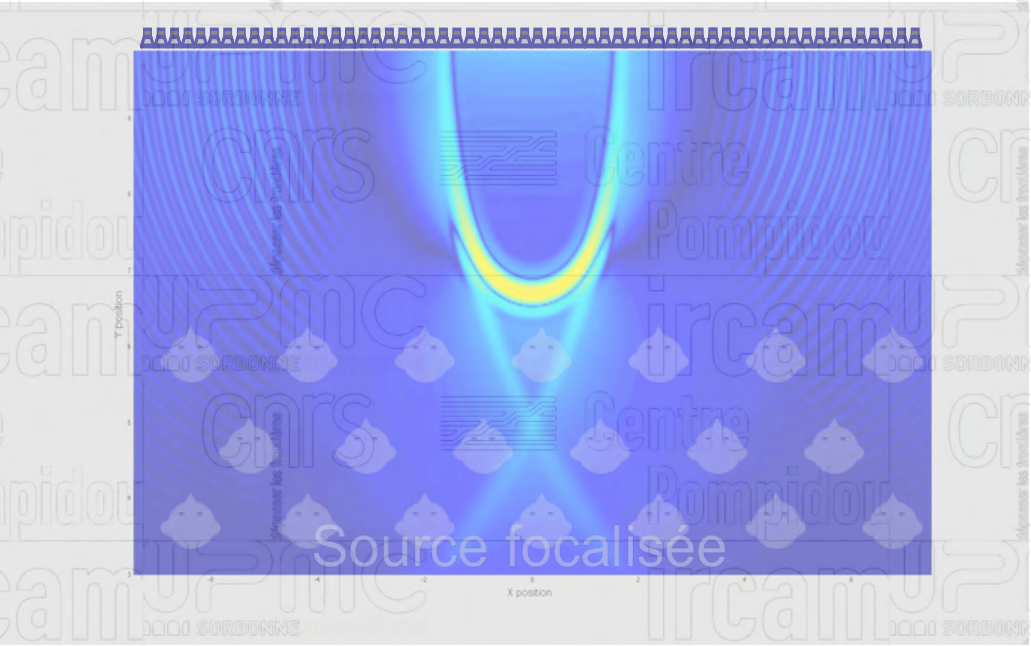
Loudspeaker array systems -WFS

simulation of a source impinging from the direction 30°



Loudspeaker array systems -WFS

simulation of a focused source located in front of the loudspeaker array [x=0; y=8]

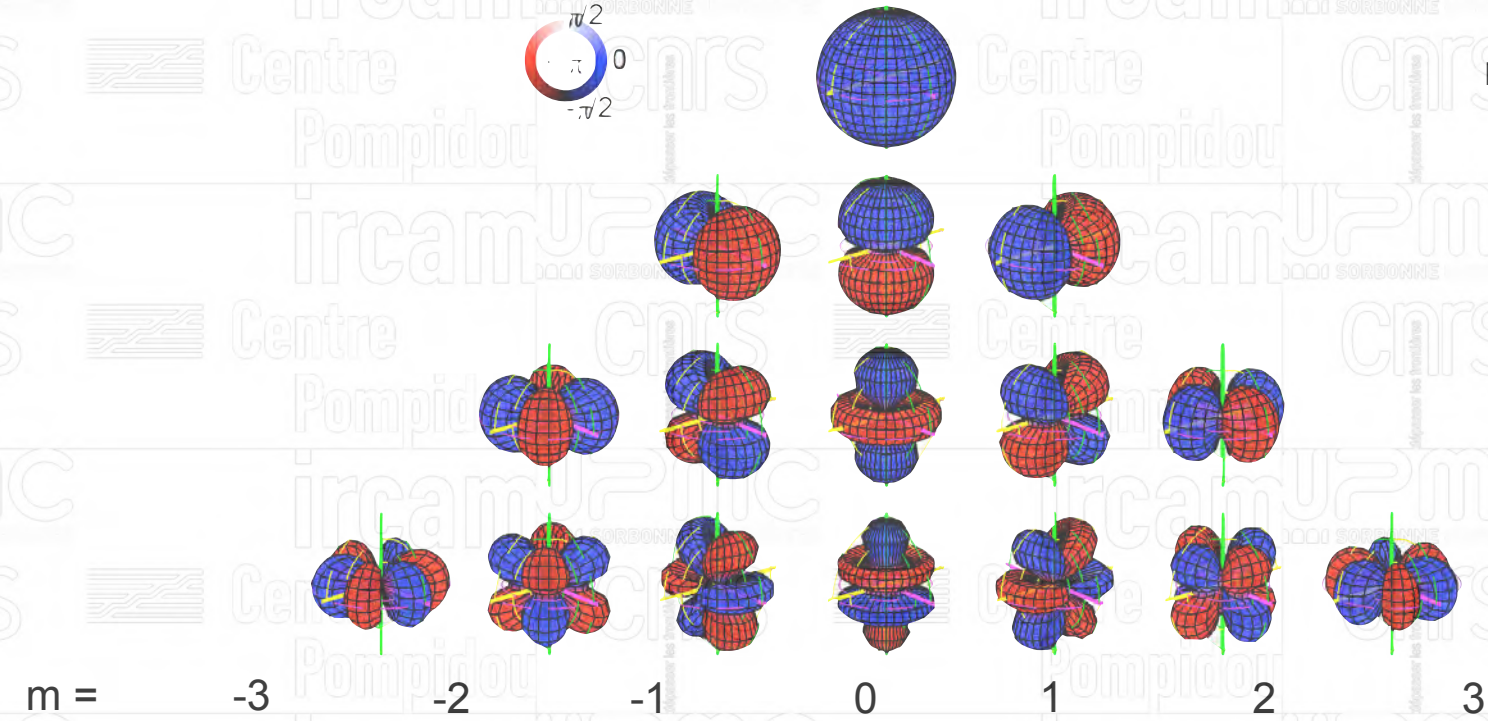


1 - Synthesis of sound source spatialization and associated technologies

- WFS
- **HOA**
- Sound installation in Espro (Ircam)

HIGHER ORDERS AMBISONICS [HOA]

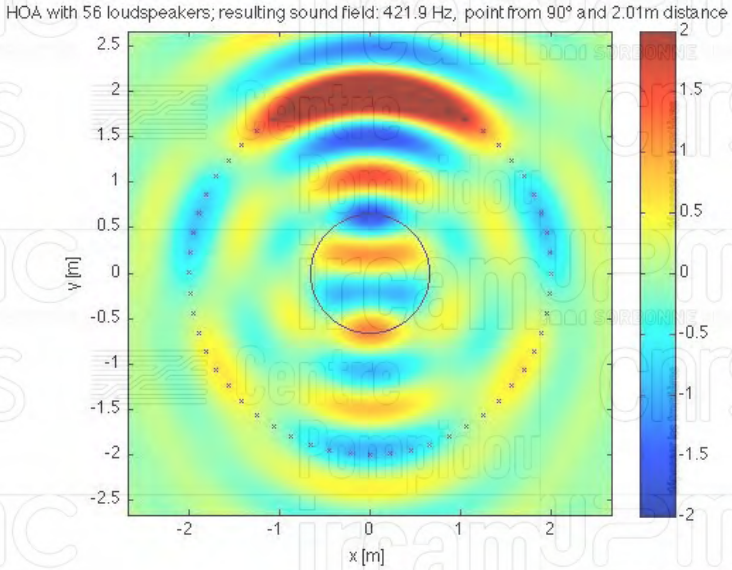
$$p(kr,\varphi,\vartheta) = \sum_{n=0}^{\infty}\sum_{m=-n}^{n}\left[b_{nm}h_n^{(1)}(kr)+c_{nm}h_n^{(2)}(kr)\right]Y_n^m(\varphi,\vartheta)$$



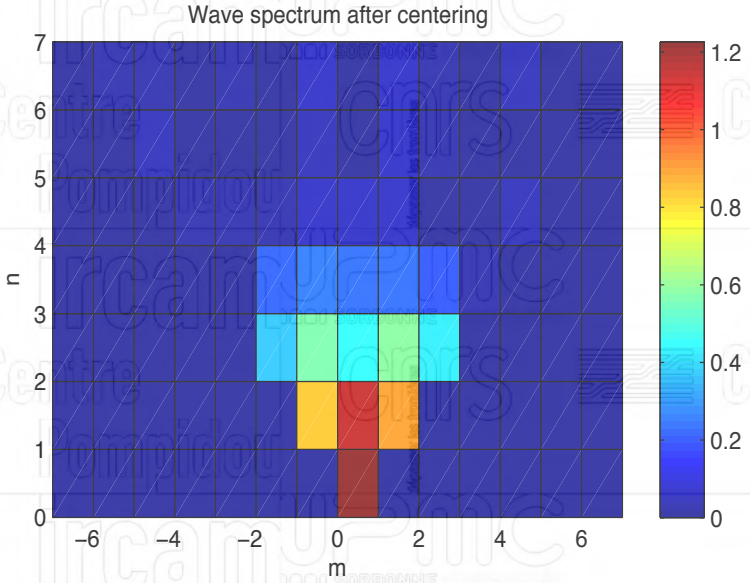
Sound Scene Synthesis

HIGHER ORDERS AMBISONICS [HOA]

- *sound field*

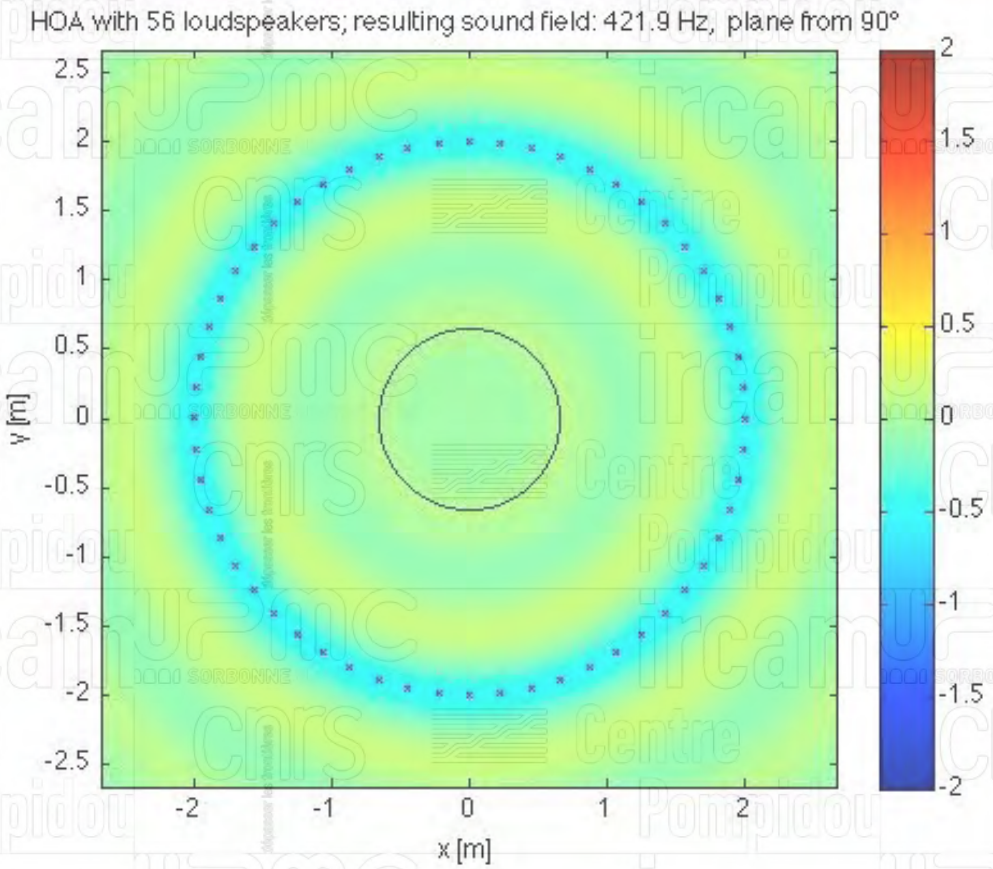


- *spherical wave spectrum*



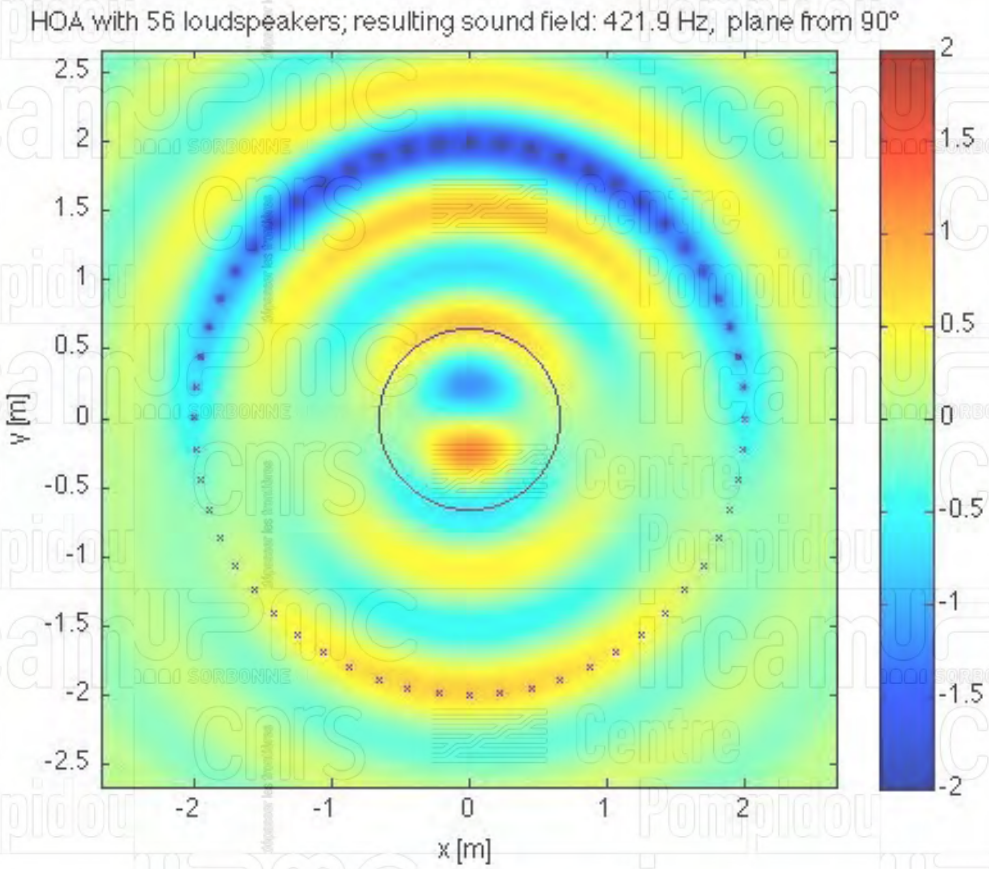
HIGHER ORDERS AMBISONICS [HOA]

- *Plane wave reconstruction with order N = 0*



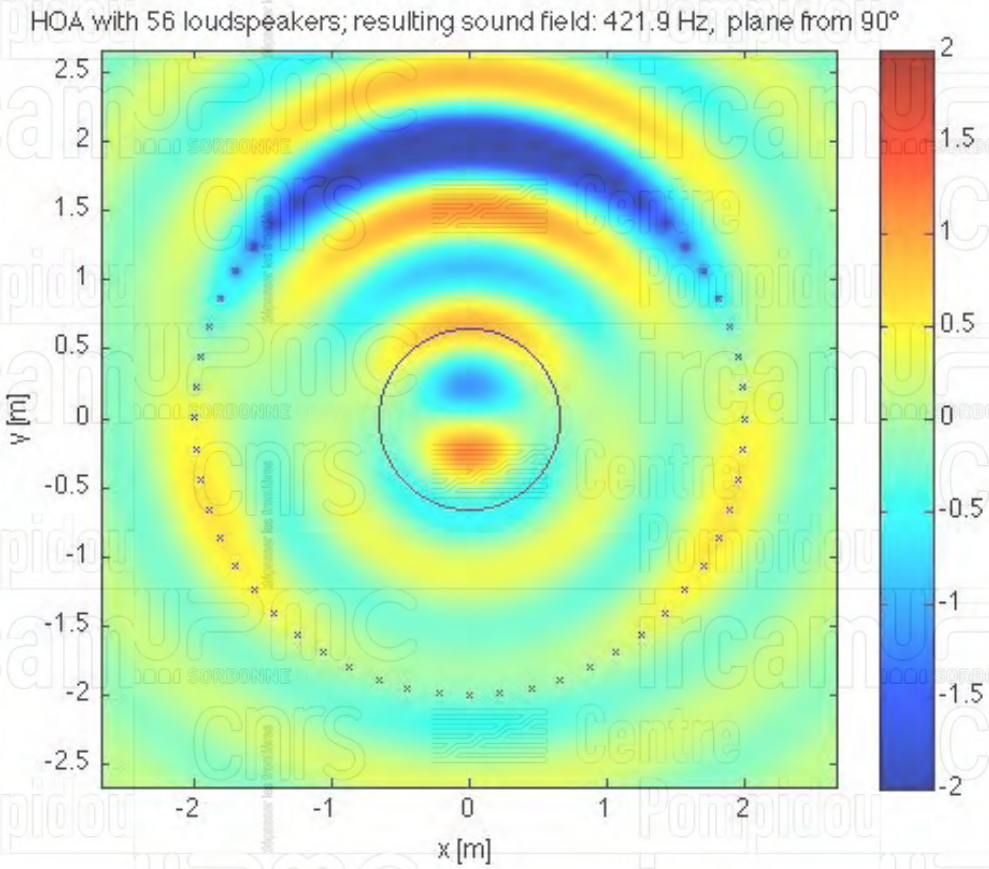
HIGHER ORDERS AMBISONICS [HOA]

- *Plane wave reconstruction with order N = 1*



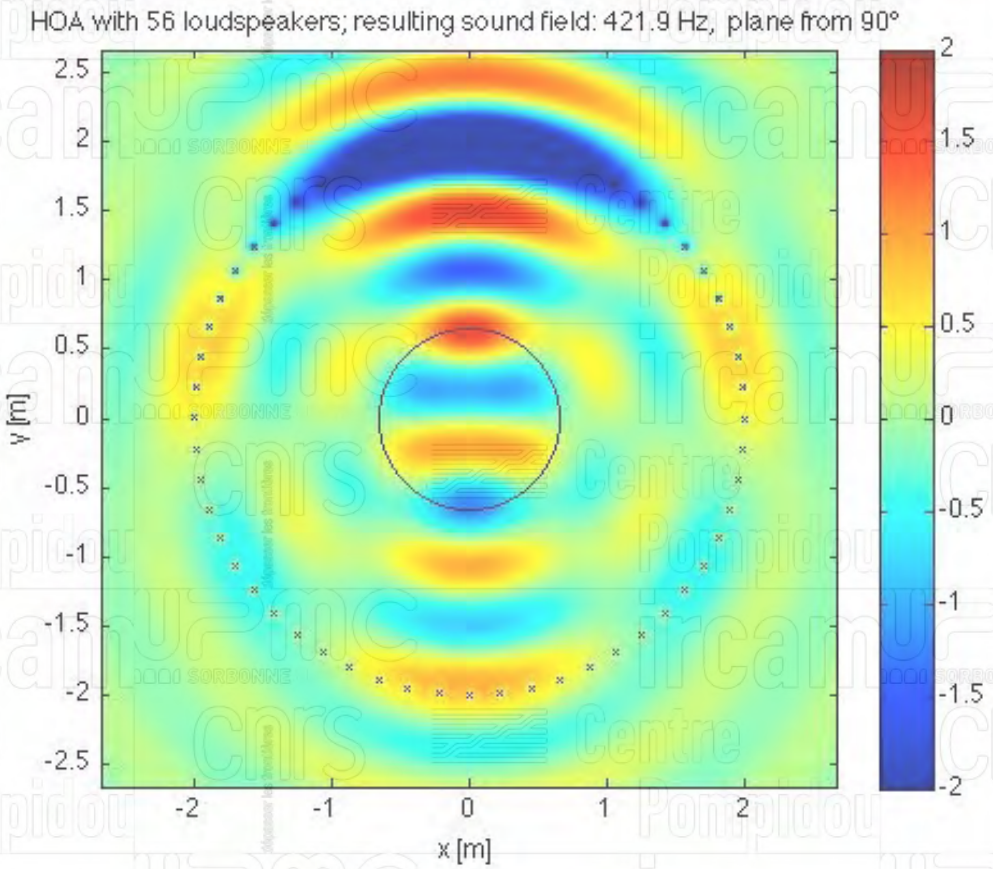
HIGHER ORDERS AMBISONICS [HOA]

- *Plane wave reconstruction with order N = 2*



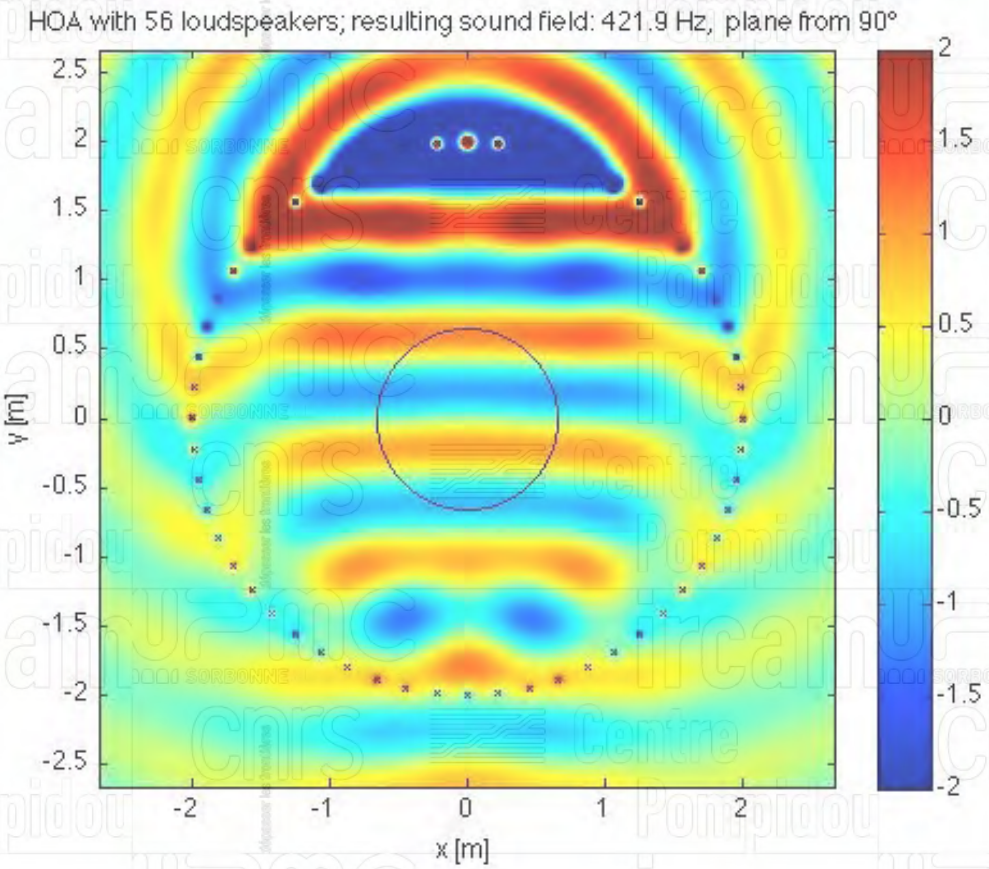
HIGHER ORDERS AMBISONICS [HOA]

- *Plane wave reconstruction with order N = 3*



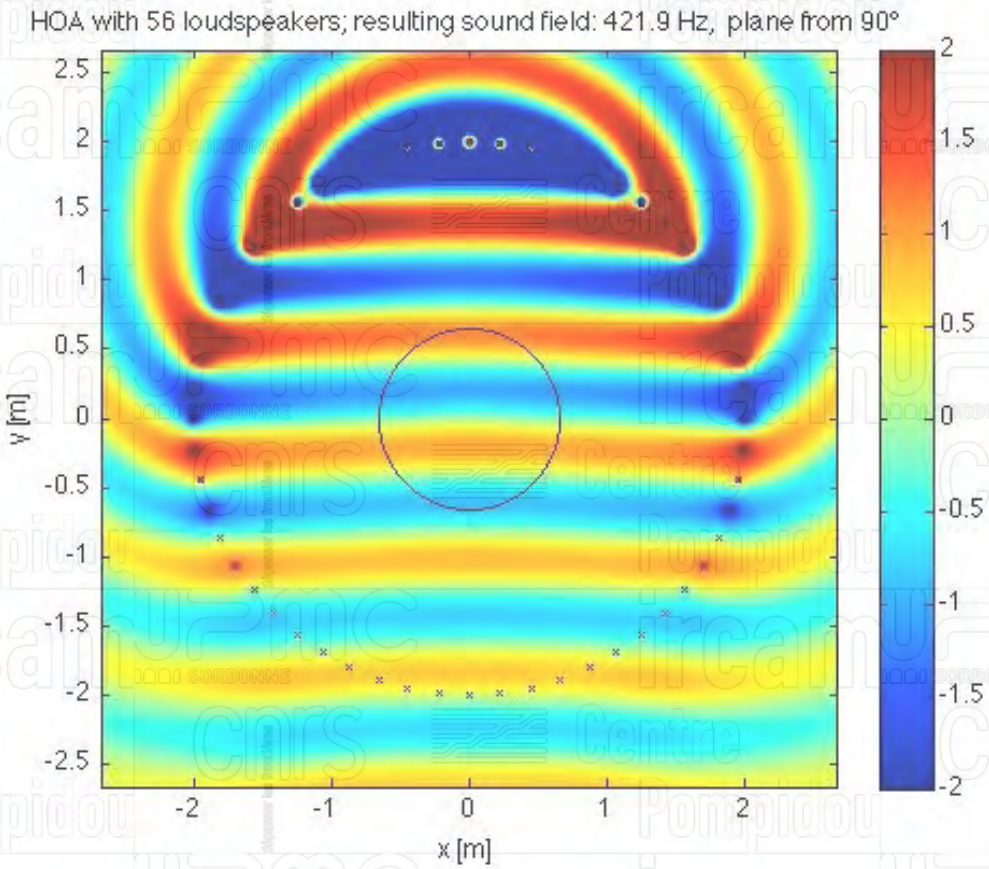
HIGHER ORDERS AMBISONICS [HOA]

- *Plane wave reconstruction with order N = 10*



HIGHER ORDERS AMBISONICS [HOA]

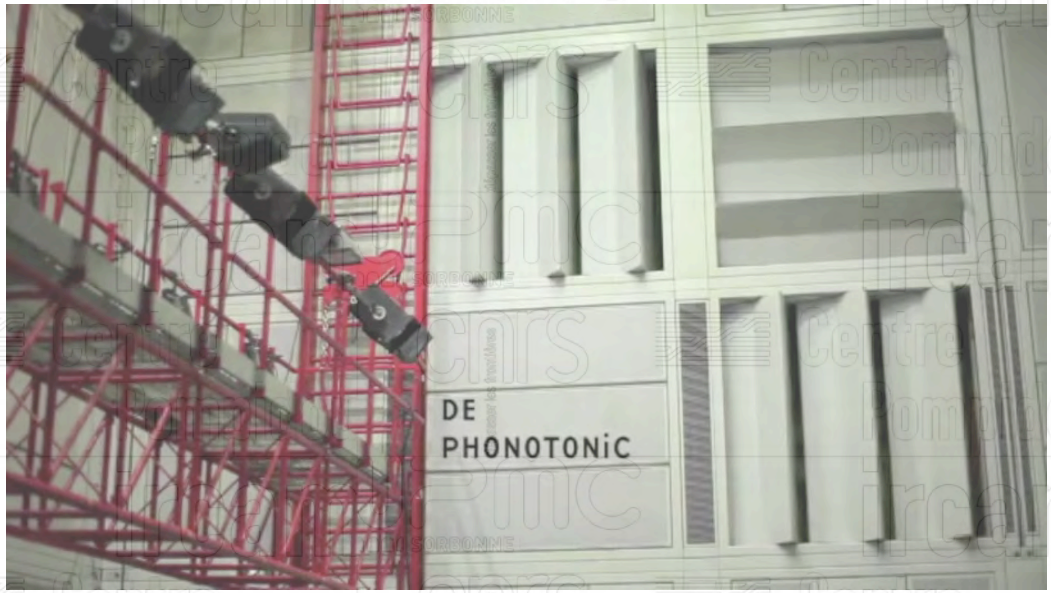
- *Plane wave reconstruction with order N = 20*



WFS and HOA in ESPRO 2.0

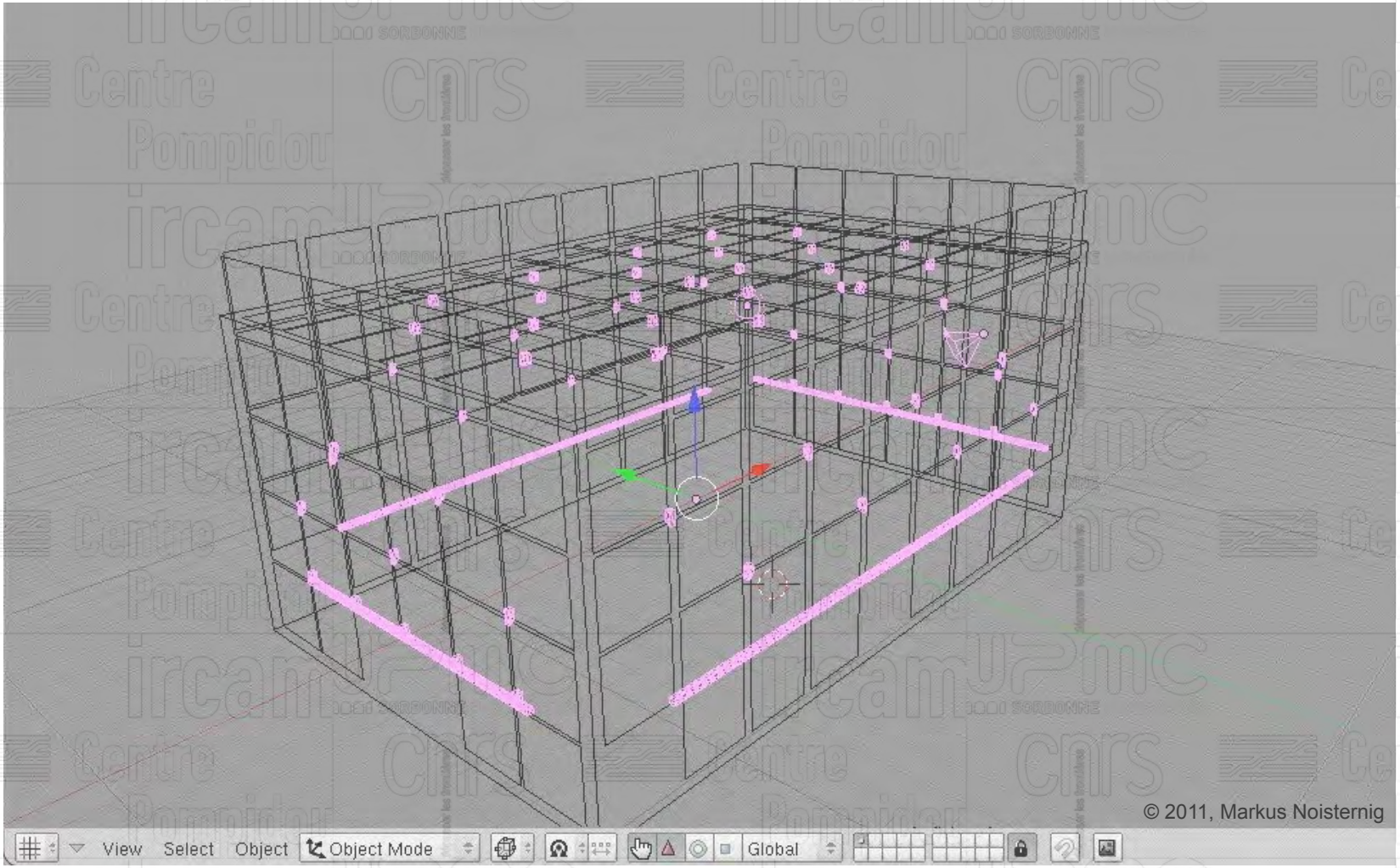
29th May 2015
ESCOLA DE COMUNICAÇÕES E ARTES
UNIVERSIDADE DE SÃO PAULO

ESPACE DE PROJECTION



- Variable acoustic concert hall at IRCAM
- Designed in 1978 by Peutz & Associés
- Provides spatial and acoustical flexibility and variability
- Rotating sound panels (absorbent, specular/diffuse reflections)
- Room size/volume: 15.5 x 24 x (0.8 - 10.5) m^3 ; 276 - 3906 m^3
- Reverberation time: T60 = 0.4s - 4s

WFS - HOA installation in ESPRO



WFS/HOA - ESPRO 2.0

- **FRONT & BACK**

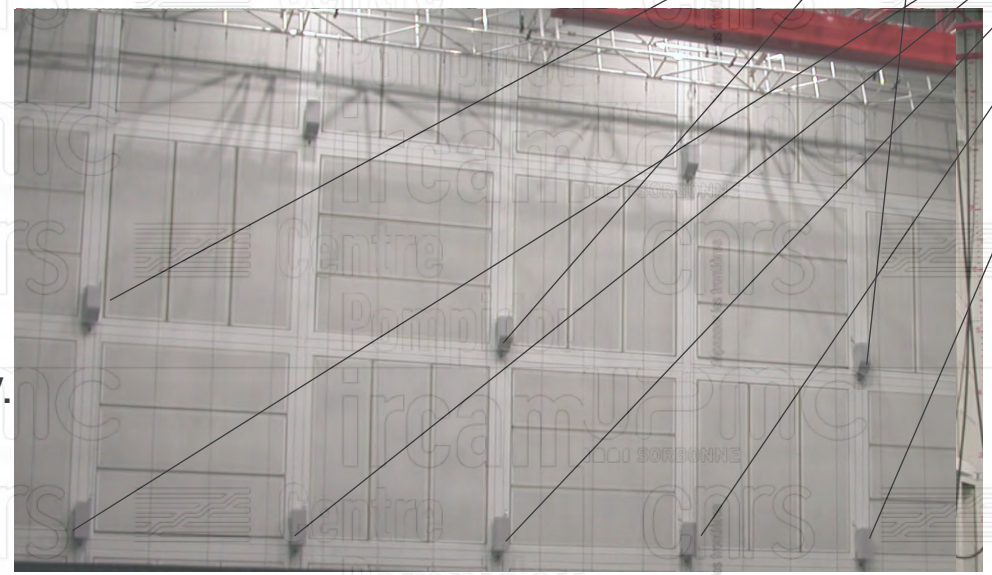
Amadeus PMX5-A/ES

Compact coaxial
active/ethersound speakers

- **SIDES + HOA**

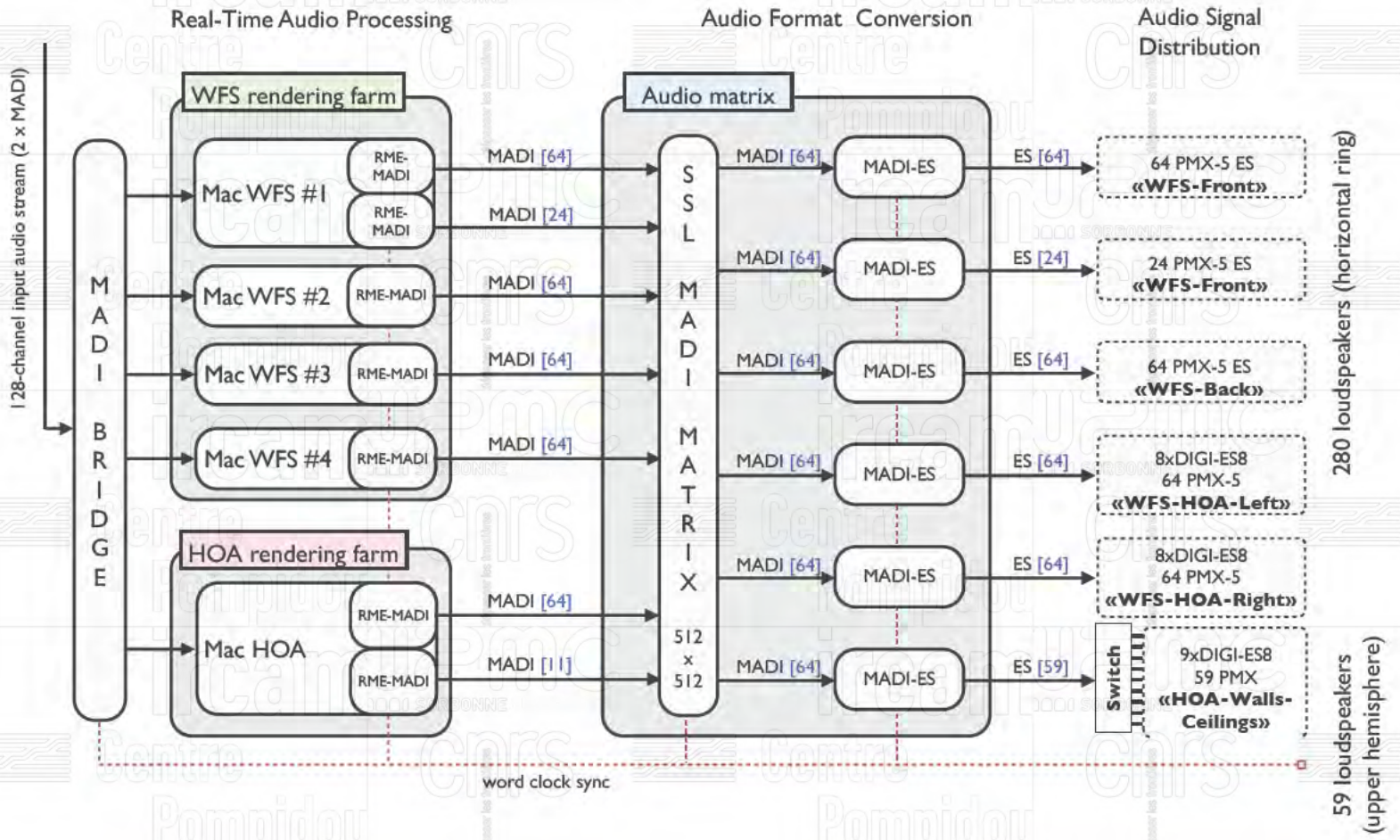
Amadeus PMX5 «Slim» (passive)

Labgruppen C10:8 class D amplifiers
Digigram ES8 Ethersound/analog conv.

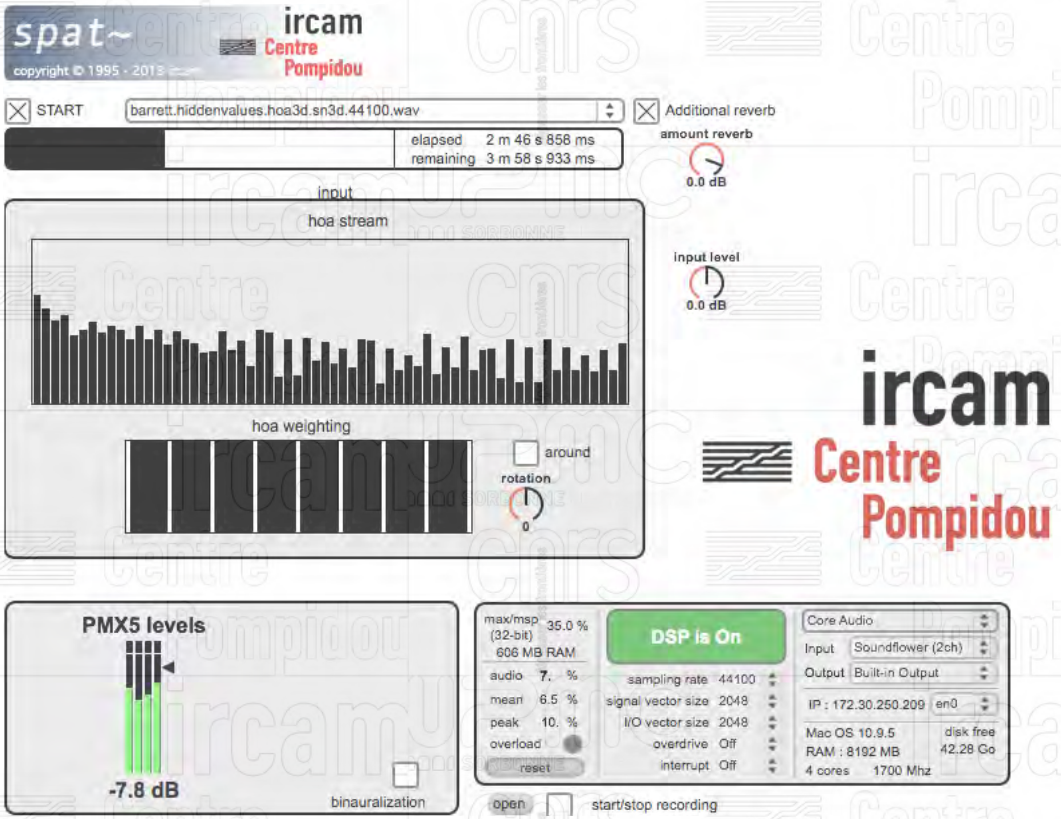


WFS/HOA - ESPRO 2.0

WFS/HOA - ESPRO 2.0



WFS/HOA - ESPRO 2.0



ircam Centre Pompidou

Hidden Values
[Optical tubes]

Natasha Barrett

Matériau sonore vocal et instrumental :

Evdokija Danajloska, soprano
Gilles Durot, percussion

Sound Scene Synthesis

FAPESP

29th May 2015

ECA ESCOLA DE COMUNICAÇÕES E ARTES
UNIVERSIDADE DE SÃO PAULO

USP

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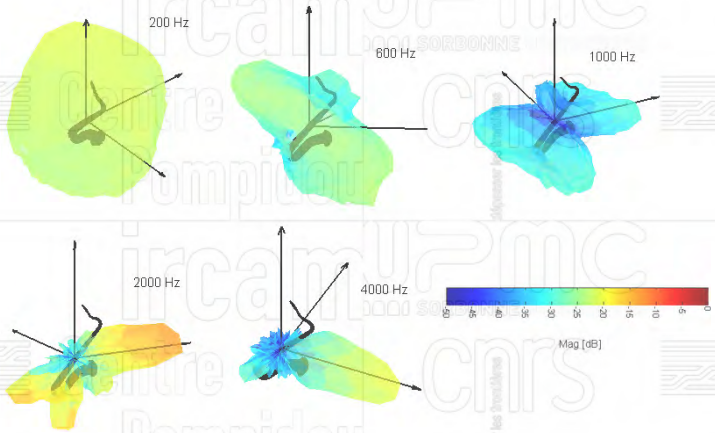
Centre Pompidou
cnrs

1 - Synthesis of sound source location and radiation

- WFS
- HOA
- Radiation synthesis

Analysis/Synthesis of radiation pattern

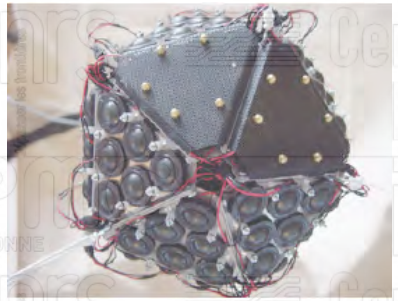
Radiation pattern measurements



Analysis/Synthesis of source radiation

Analysis of radiation patterns
Spatiotemporal sound analysis of instruments

Synthesis of radiation patterns
Spherical loudspeaker arrays



IRCAM (P.Derogis et al.)
IEM (F. Zotter et al.)
CNMAT (Avizienis et al.)
Ben Gurion Univ. (B. Rafaely et al.)
Minas Gerais (A.M Pasqual)

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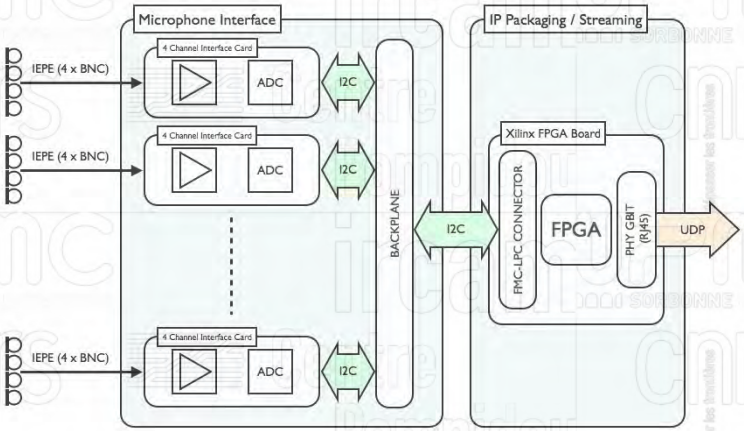
Spherical Microphone Arrays

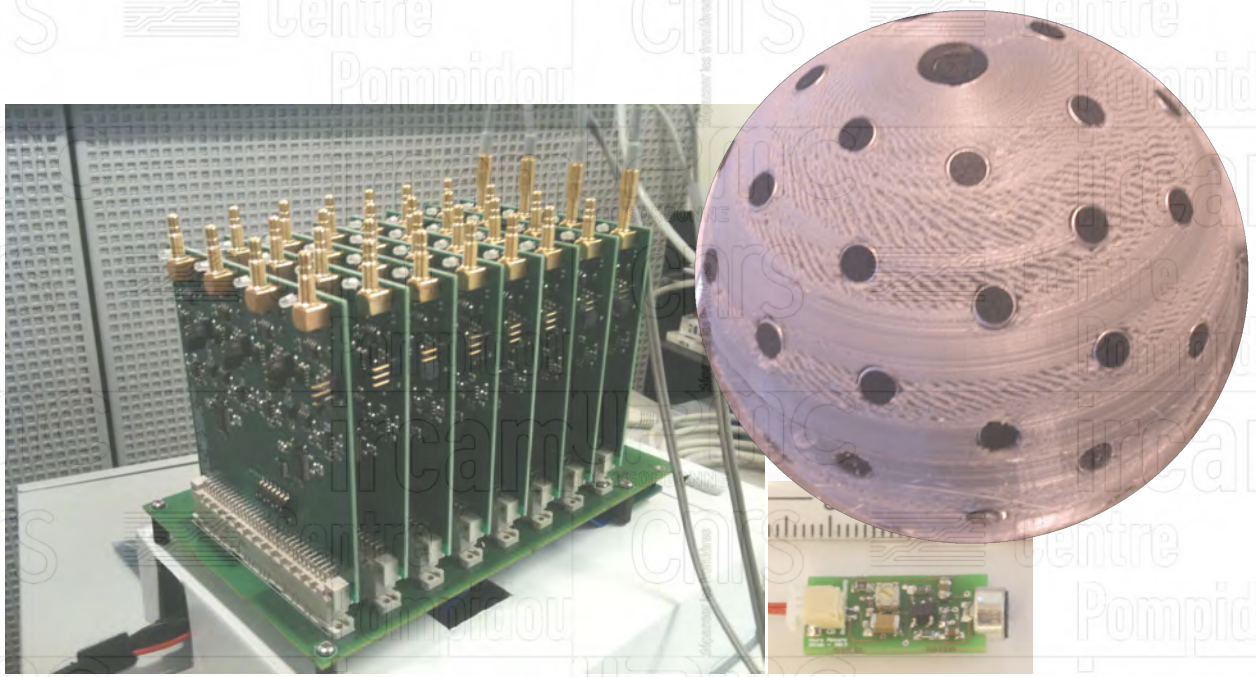
Soundfield

EigenMike® MH
acoustics

10th order microphone
Tohoku University

IRCAM SPHERICAL MIC-ARRAY





after M. Noisternig

Sound Scene Analysis

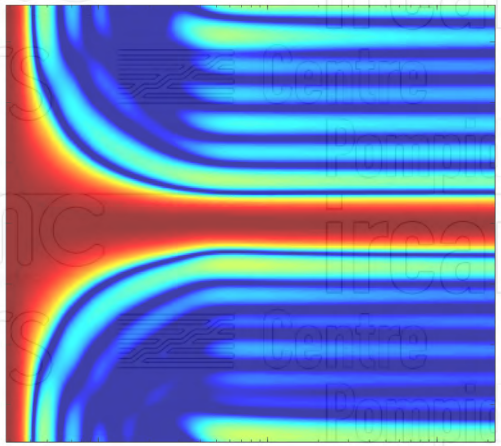
SPHERICAL HARMONIC SERIES / HOA

$$\begin{aligned}\mathbb{P}(k,r,\theta,\phi) &= \sum_{n=0}^{\infty}\sum_{m=-n}^{n}\left(\int_0^{2\pi}\int_0^{\pi} Y_n^m(\theta,\phi)a(\theta,\phi,k)\sin\theta d\theta d\phi\right) H_n(k,r,r_s)Y_n^m(\theta,\phi)\\ &= \sum_{n=0}^{\infty}\sum_{m=-n}^{n} a_{nm}(k)H_n(k,r,r_s)Y_n^m(\theta,\phi)\\ &= \sum_{n=0}^{\infty}\sum_{m=-n}^{n} p_{nm}(k,r,r_s)Y_n^m(\theta,\phi)\end{aligned}$$

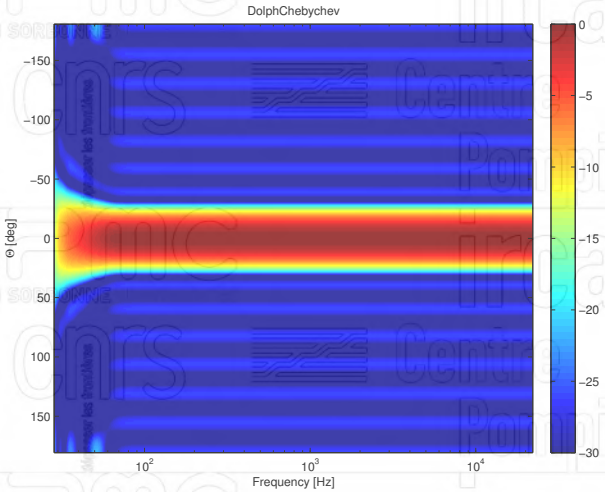
- $p_{nm}(k,r,r_s)$ are the pressure SH coefficients.
- The holographic function $H_n(k,r,r_s)$ is a known function and depends on the sphere type (e.g. rigid sphere, open sphere).
- $a_{nm}(k)$ is the plane-wave amplitude density function, which is also referred to as higher-order Ambisonics (HOA) coefficients.

BEAMFORMER EXAMPLES

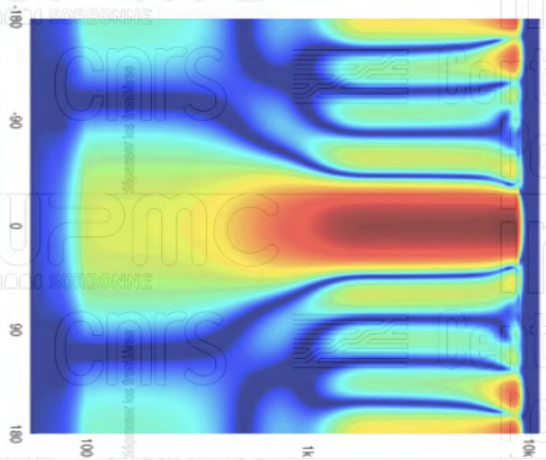
Maximum WNG

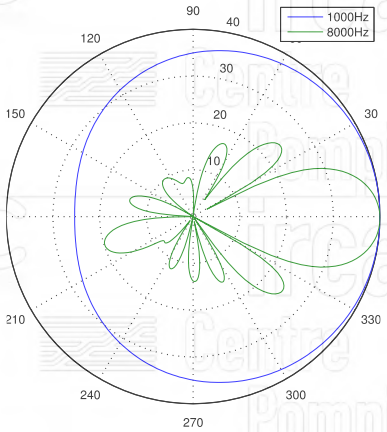


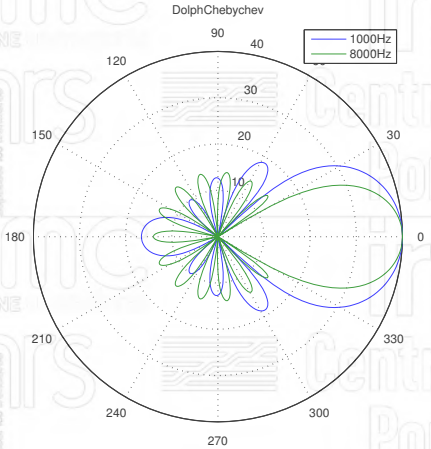
Dolph-Chebychev

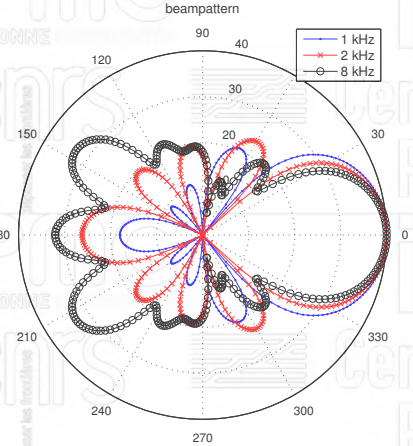


modal beamformer



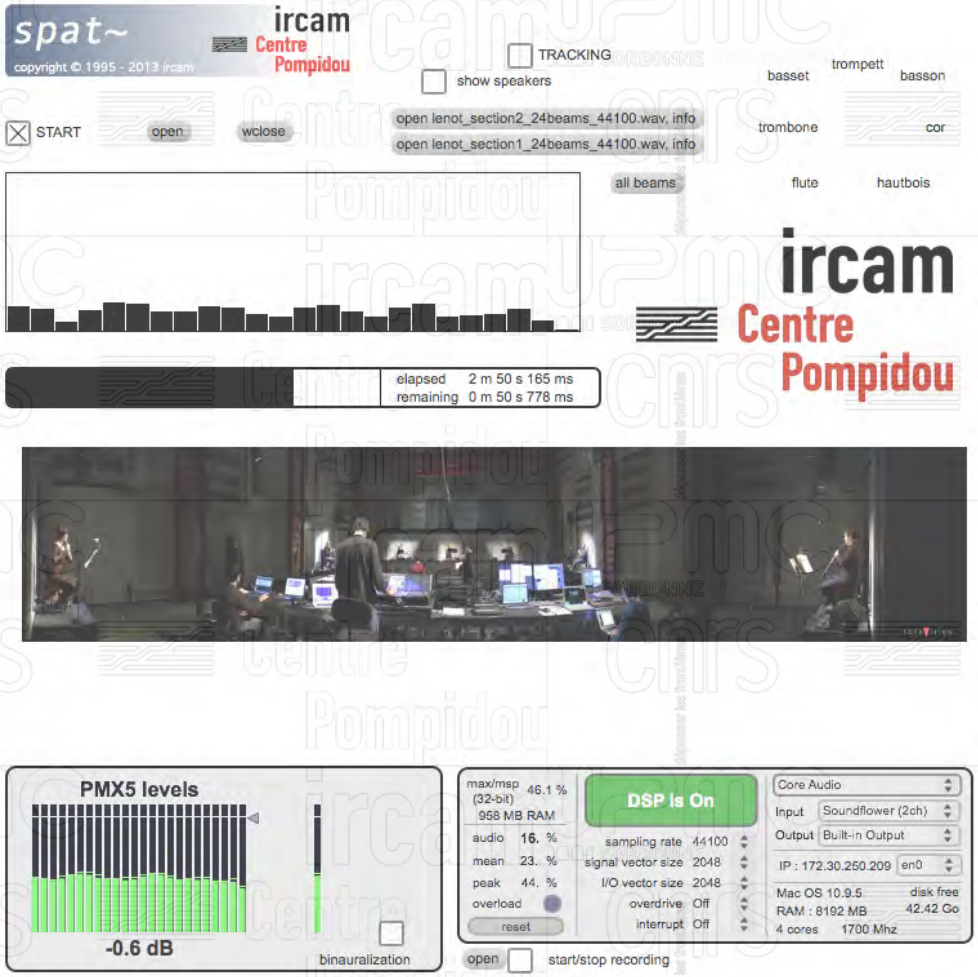


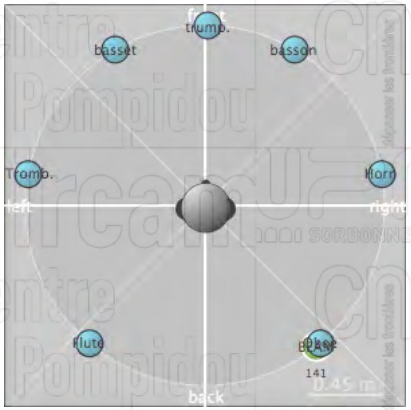




Sound Scene Analysis

Real-Time Beamforming





Isis et Osiris

Jacques Lenot

Sound Scene Analysis

29th May 2015

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MOTIVATIONS

Enhanced Room acoustics measurements / analysis

- ISO3382, limited spatial analysis, omni source, 1st order microphone,
- Augmenting auralization experience through DRIR measurements with SMAs
  - encoding of the spatial information
  - decoding over large variety of rendering system (incl. binaural)
- Augmenting auralization experience through DRIR measurements with SLAs
  - synthesing the room effect according to the directivity pattern of instruments
- Extension of Room Acoustics perceptual models

Measurement of DRIR (Directional Room Impulse Response) with Spherical Microphone Array (SMA)

DRIR measurements using Spherical microphone arrays (SMAs)

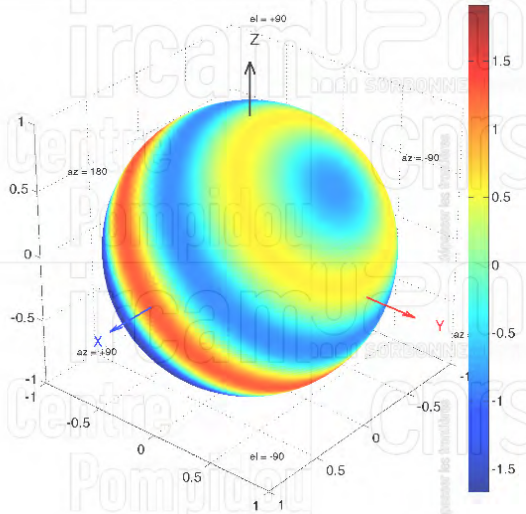
[Gover et. Al, JASA, 2002],
[Rafaely, IEEE, 2005],
[Park and Rafaely, JASA, 2005],
[Teuch and Kellerman, IACSSP 2008],
[Sun et al, JASA 2012].

SPHERICAL MIC-ARRAY

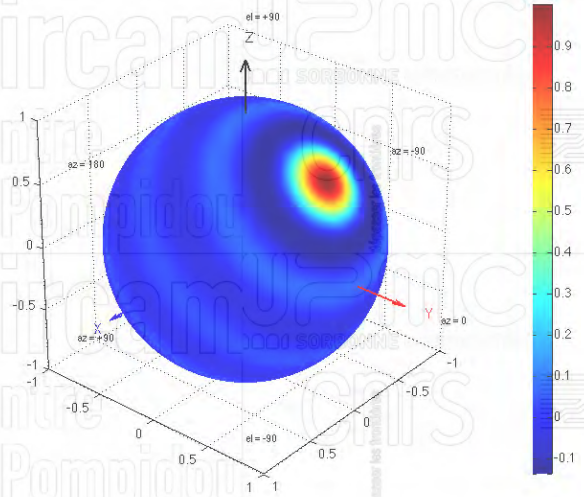
after T. Szpruch

a = 0,04m
f = 12,8kHz

sound field



plane wave decomposition



Sound Scene Analysis

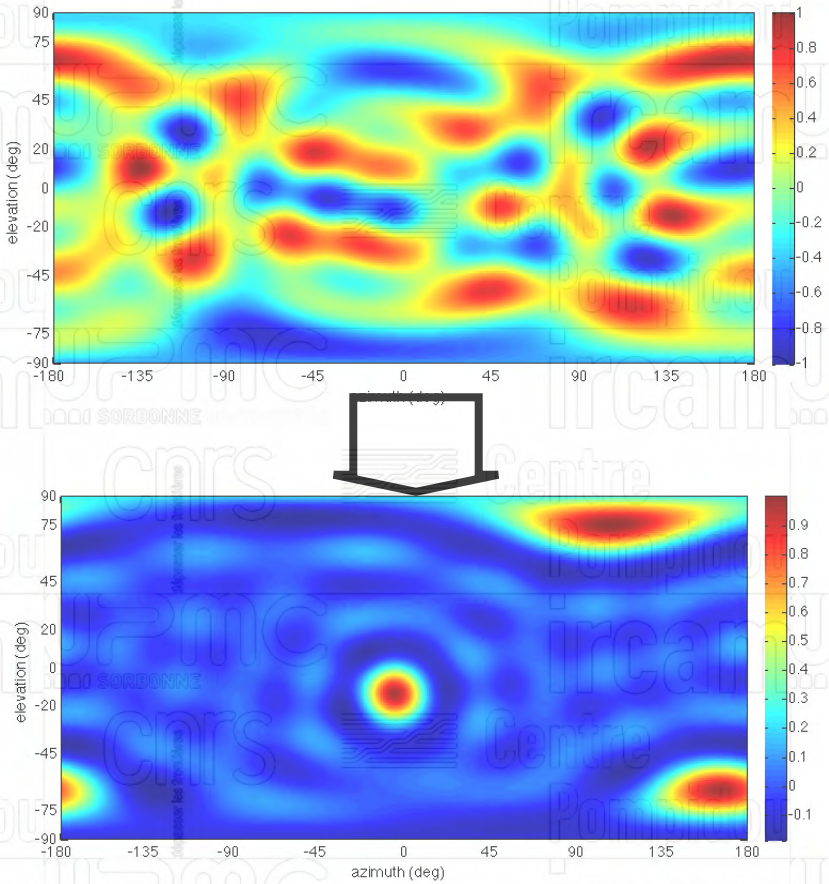
SPHERICAL MIC-ARRAY

after T. Szpruch

3 plane waves

N = 10; *kr* = 9

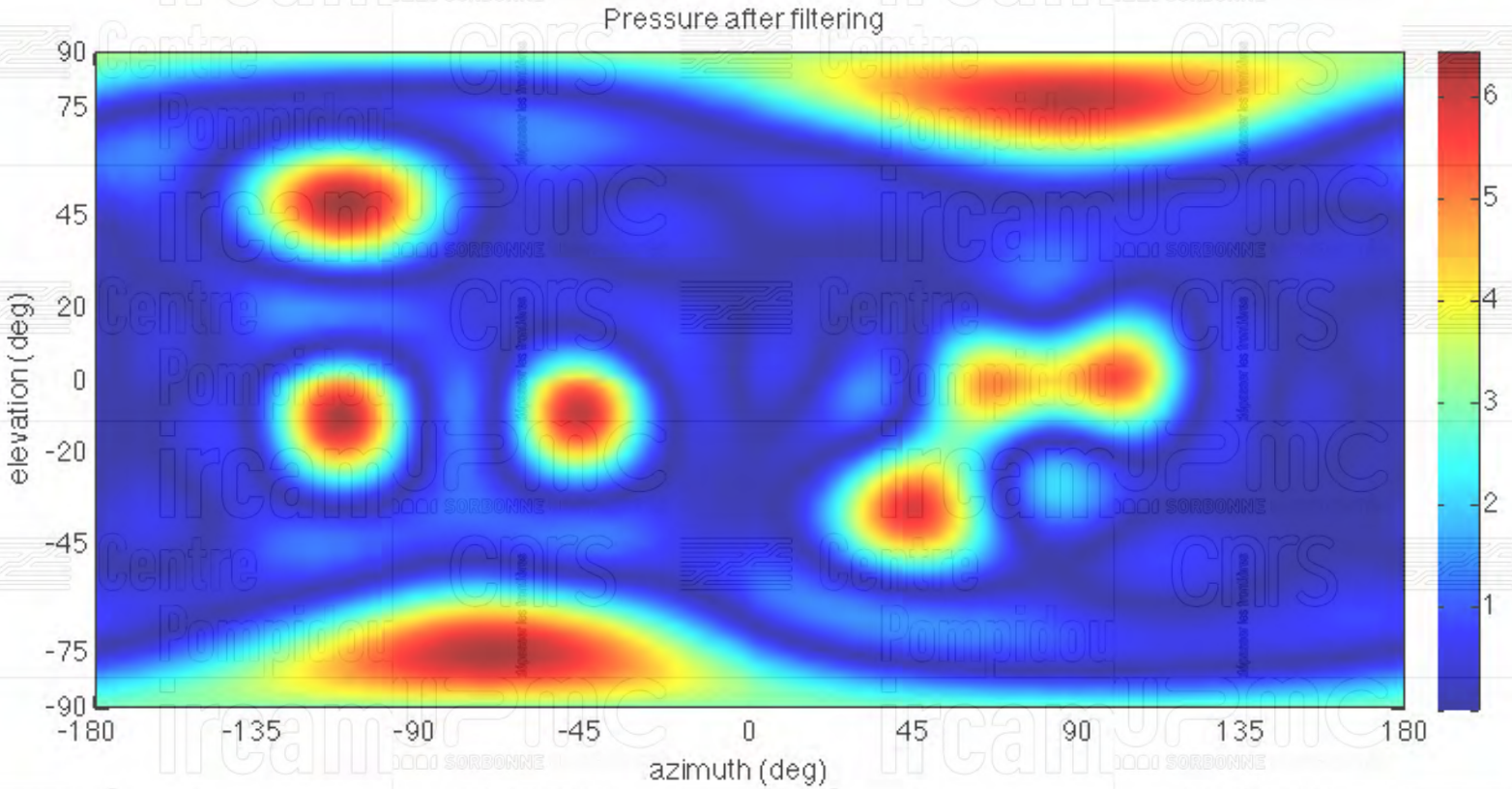
sound field



plane wave decomposition

SPHERICAL MIC-ARRAY

after T. Szpruch



Measurement of DRIR with Spherical Loudspeaker Array (SLA)

Credit Angelo Farina

DRIR measurements using Spherical loudspeaker arrays (SMAs)

[Farina et al. JASA 2006].
[Pollow et al. ICA 2013].

Measurement of DRIR with SLAs and SMAs

Design constraints on both SLAs and SMAs

- Spatial aliasing
  - kr < N
- spatial sampling scheme
  - conditioning, orthogonality of discrete SH
- sensor mismatch
  - transducer response and position
  - rigid sphere assumption
- soft limiting of inverse holographic function
  - band limitation

Measurement of DRIR with SLAs and SMAs

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- sensor mismatch
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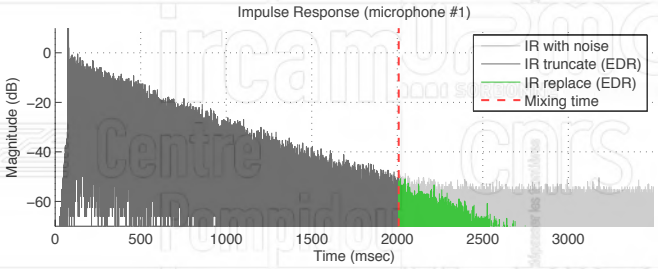
  - rigid sphere assumption
- soft limiting of inverse holographic function
  - band limitation

DRIR late reverberation denoising



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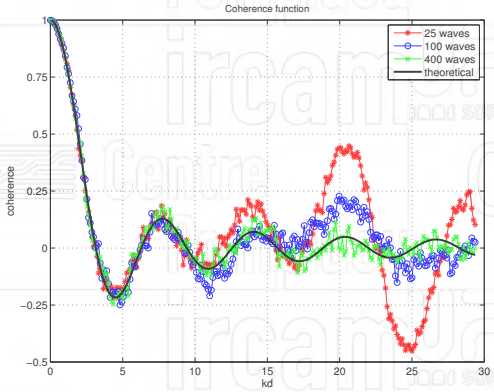
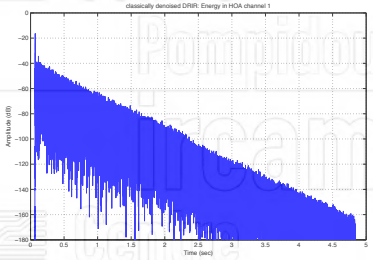
DRIR late reverberation denoising

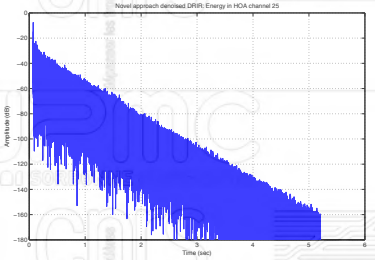


Simulation of diffuse field using 400 uncorrelated plane waves.

Applied to a virtual model of the SMAs



HOA order 0



HOA order 25

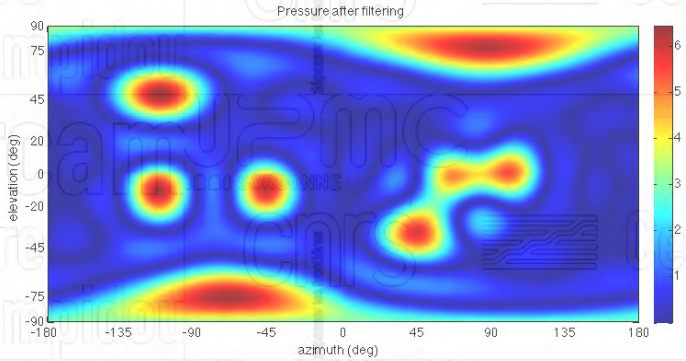
Sound Scene Analysis

Measurement of DRIR with SLAs and SMAs

On going analysis of SMAs/SLAs MIMO system properties

H. Morgenstern Phd
Univ. Ben Gurion (B. Rafaely)
IRCAM (M. Noisternig)

- Theoretical formulation of a MIMO system
- MIMO system model for joint SMA-SLA processing
- Studied for both free field conditions and for rooms
- Link between system rank and # of reflections
- Analysis of DRIR, providing both DORs and DOAs
- Method for joint SMA-SLA design



Sound Scene Analysis

Measurement of DRIR with SLAs and SMAs

Measurement campaign in french and european theatres/ concert halls

F. Leão Figueiredo post-doc [FAPESP]
Univ. São Paulo (F. Iazzetta)
Univ. Parma (A. Farina)
UPMC (JD Polack)
IRCAM

Measurement of DRIR with SLAs and SMAs

Philharmonie 1

Philharmonie 2

Auditorium RadioFrance

Théâtre de la Ville

Bastille, Garnier, Pleyel, Auditorium Louvre, Orsay, Chapelle de Versailles

Berlin, MusikVerein, Concertgebouw

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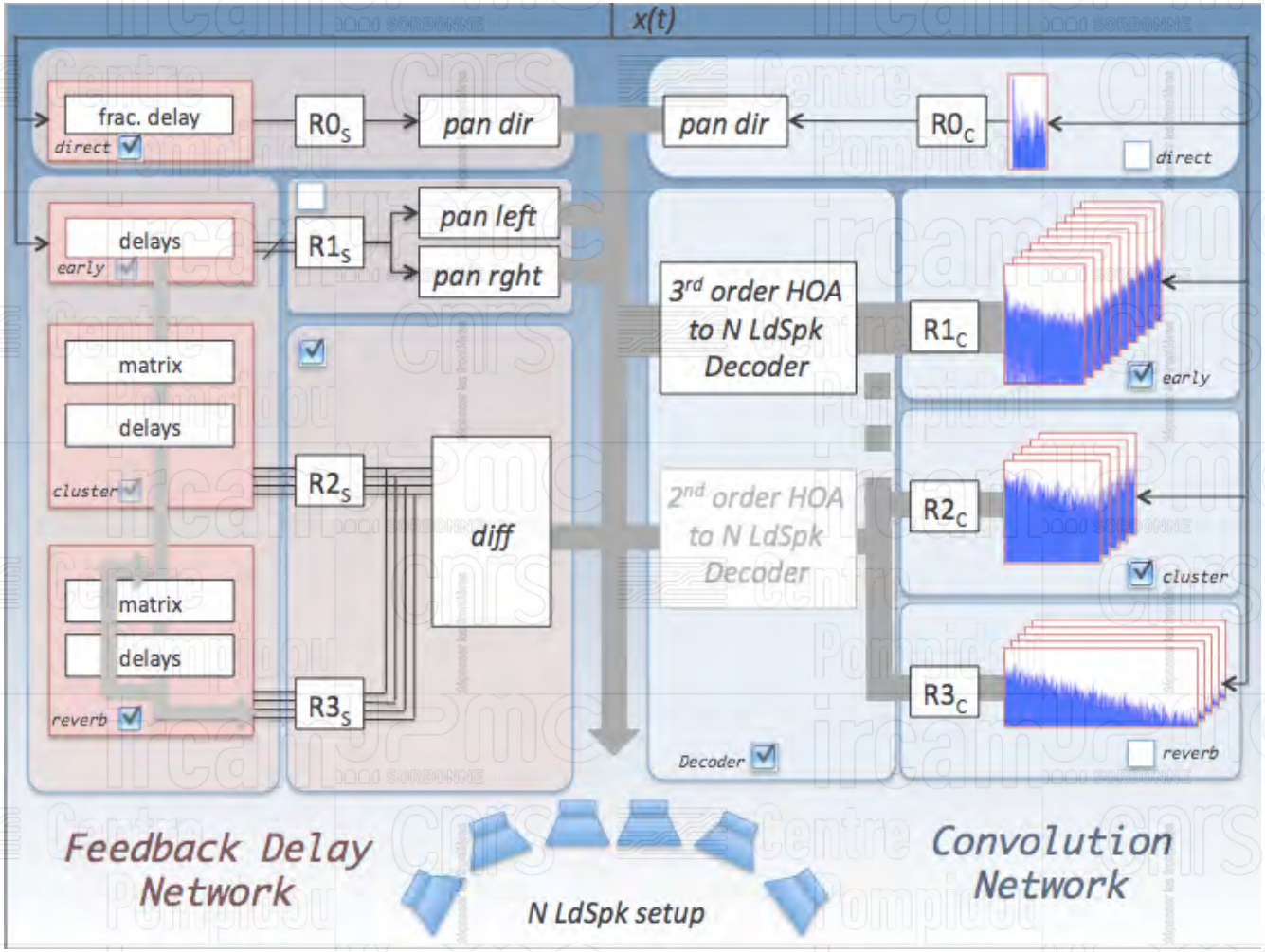
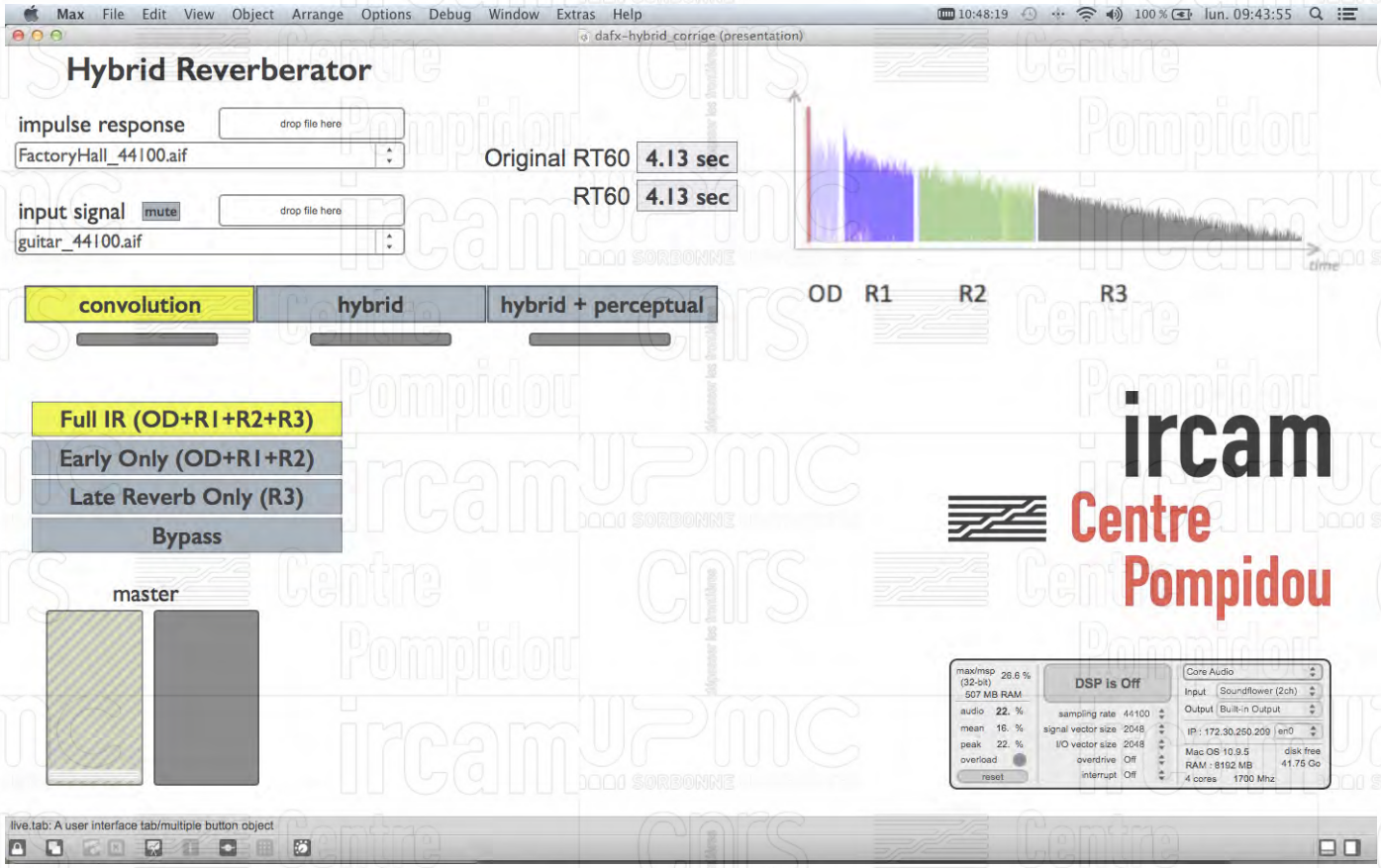
HYBRID REVERBERATION



HYBRID REVERBERATION



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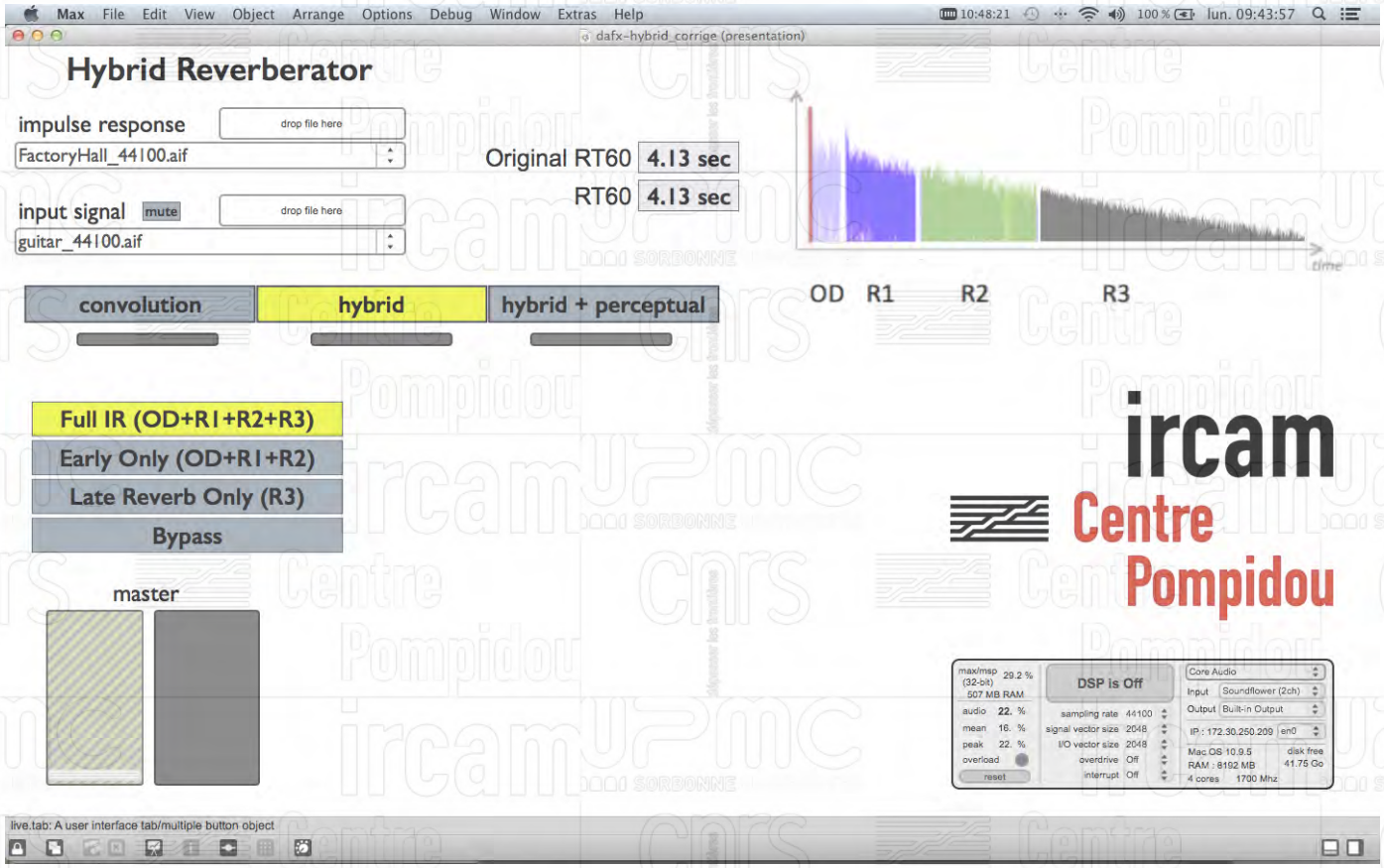
Sound Scene Analysis

HYBRID REVERBERATION



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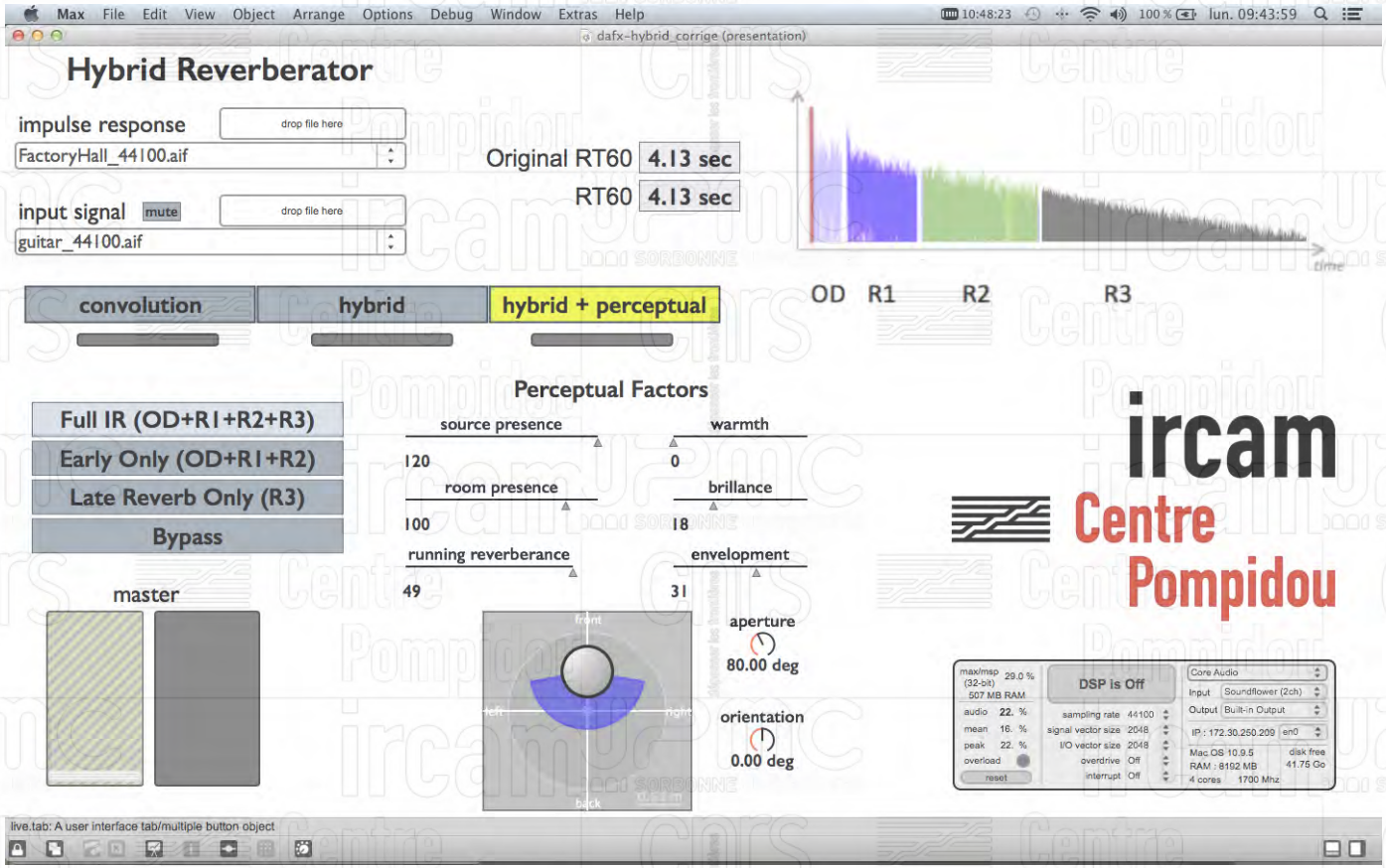
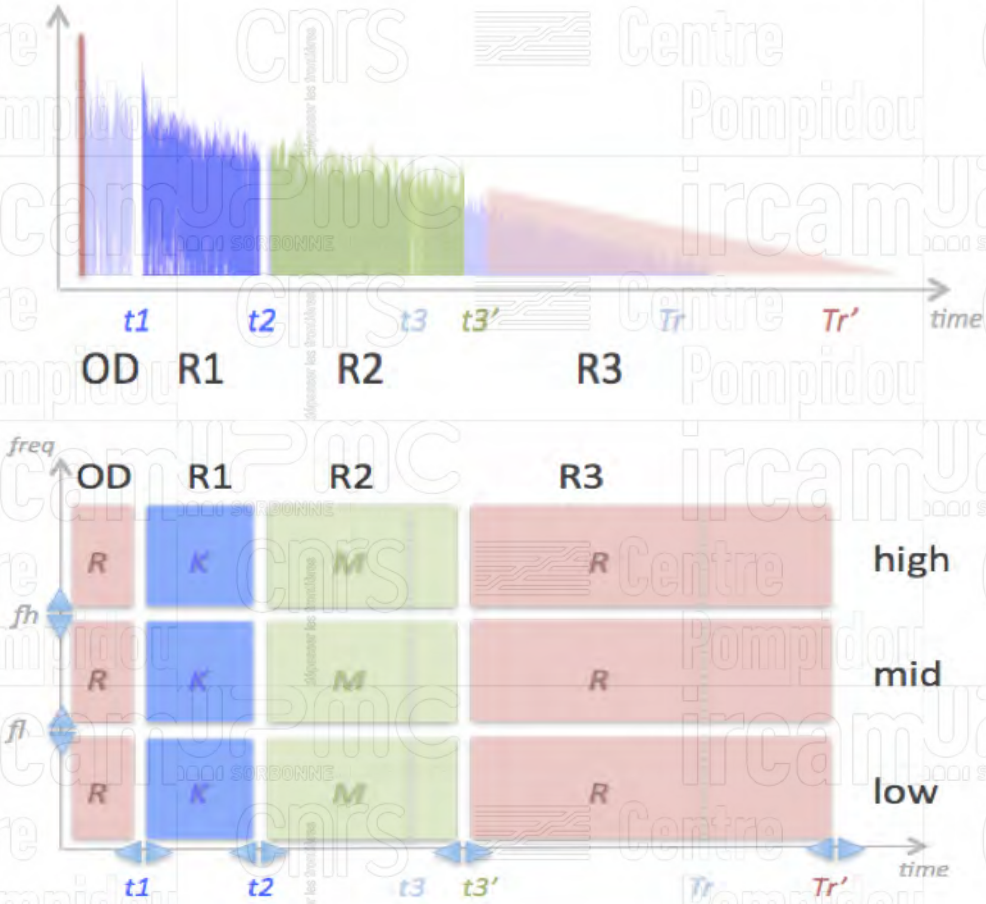
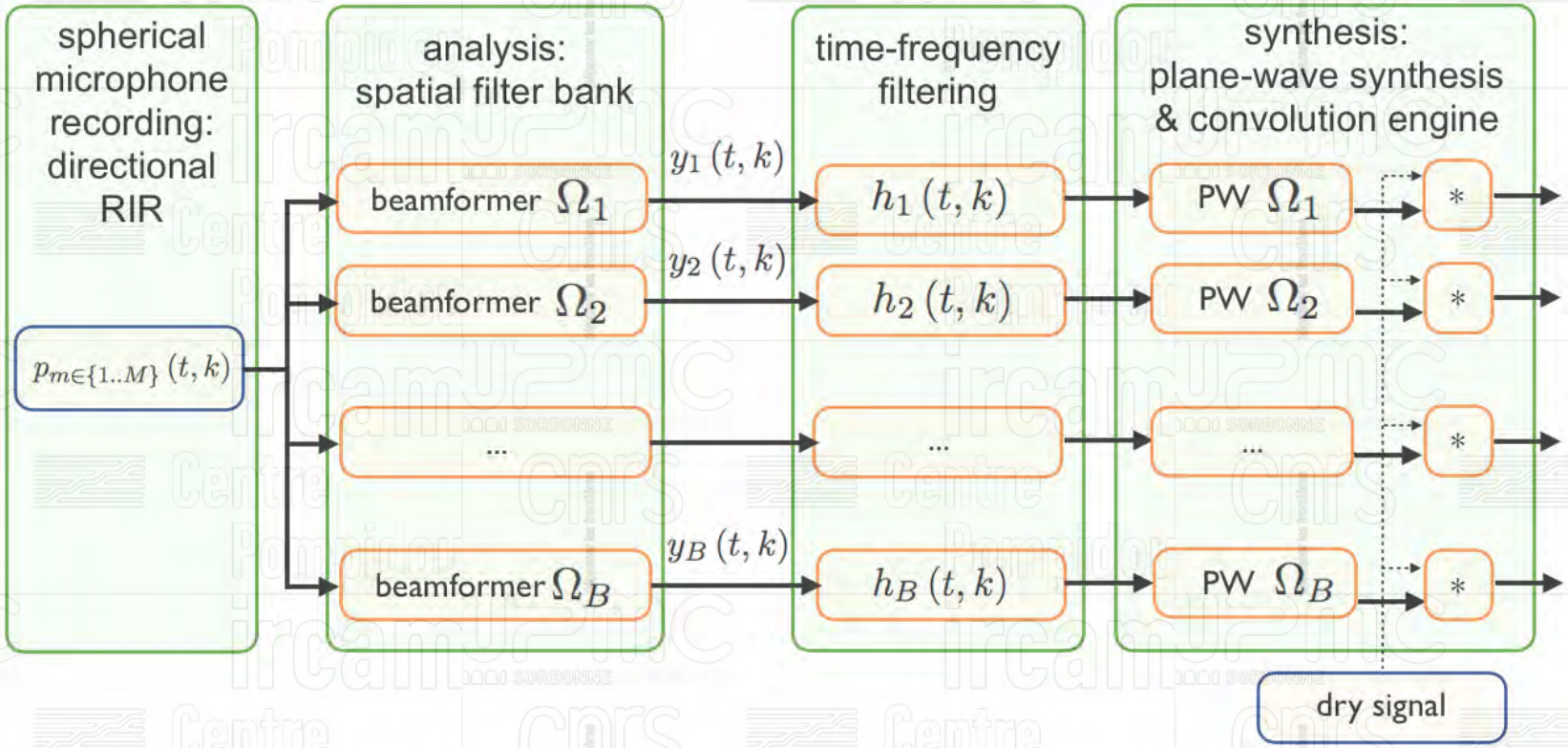
HYBRID REVERBERATION



PERCEPTUAL MODEL

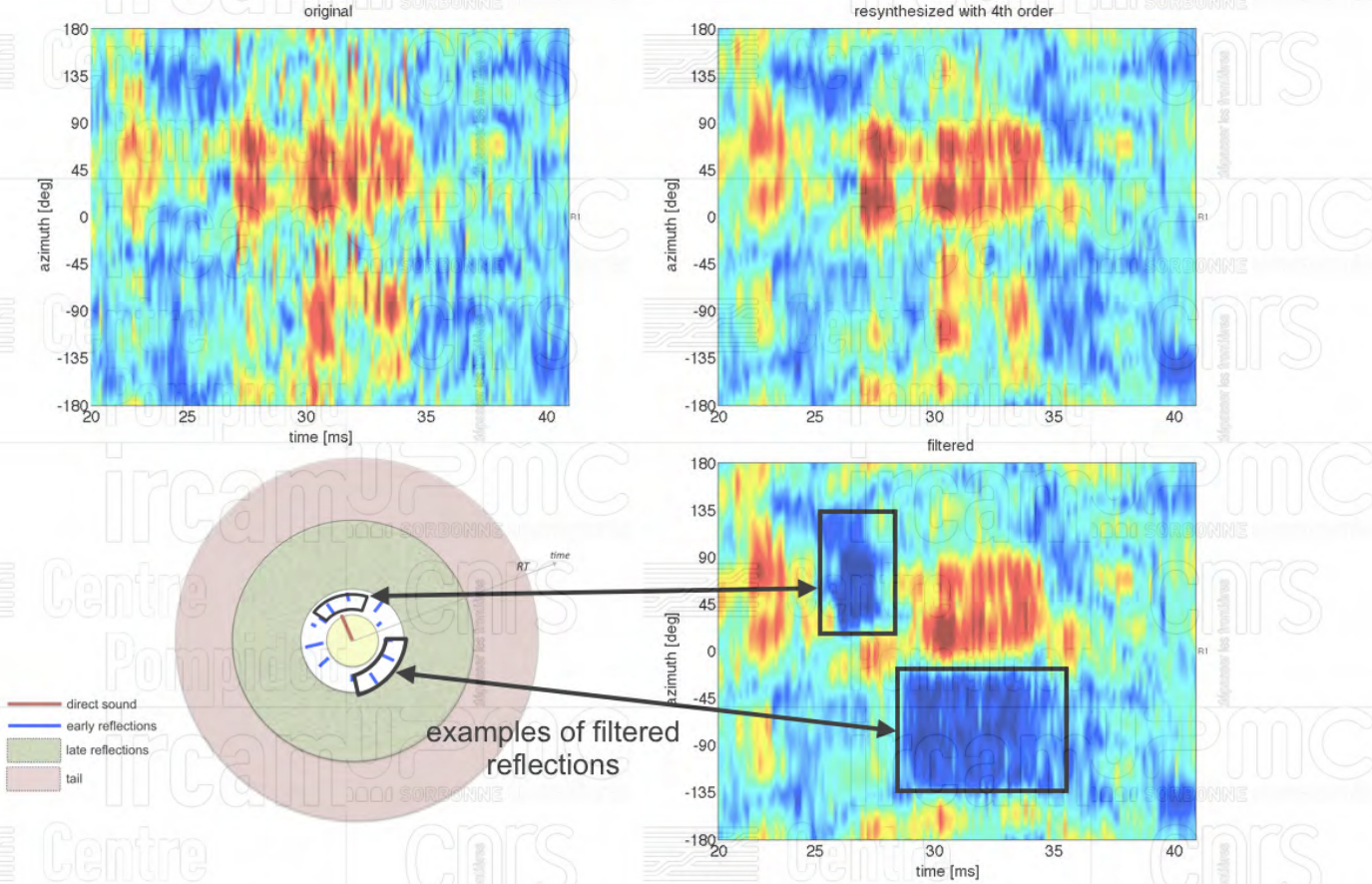


TIME-FREQUENCY-SPACE FILTERING



T. Carpentier, T. Szpruch, M. Noisternig, O. Warusfel, Parametric control of convolution based room simulator ISRA, Toronto, June 2013

TIME-FREQUENCY-SPACE FILTERING



T. Carpentier, T. Szpruch, M. Noisternig, O. Warusfel, Parametric control of convolution based room simulator ISRA, Toronto, June 2013

Sound Scene Analysis

Selected bibliography on Sound Field Analysis

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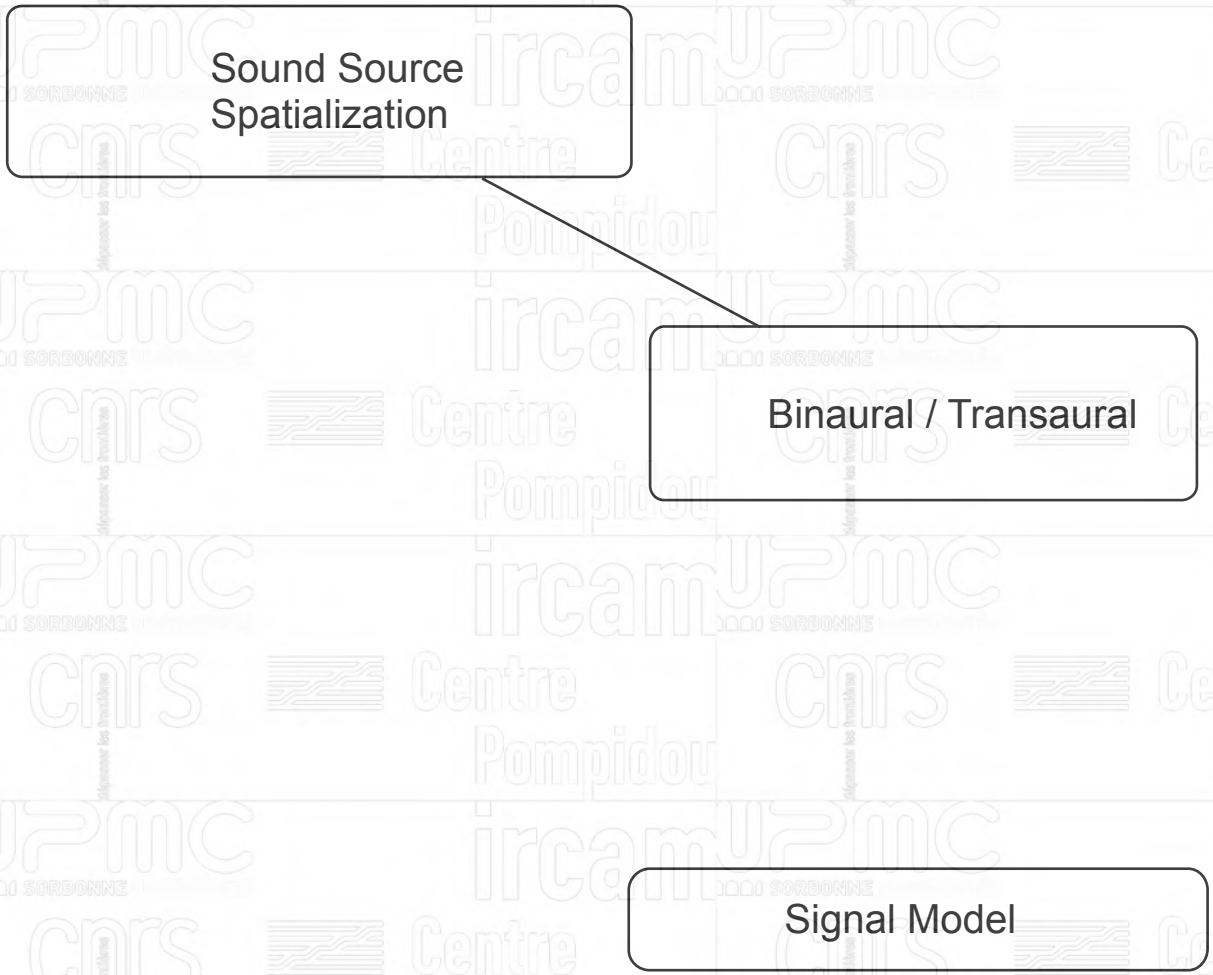
3 - 3D Binaural Broadcast

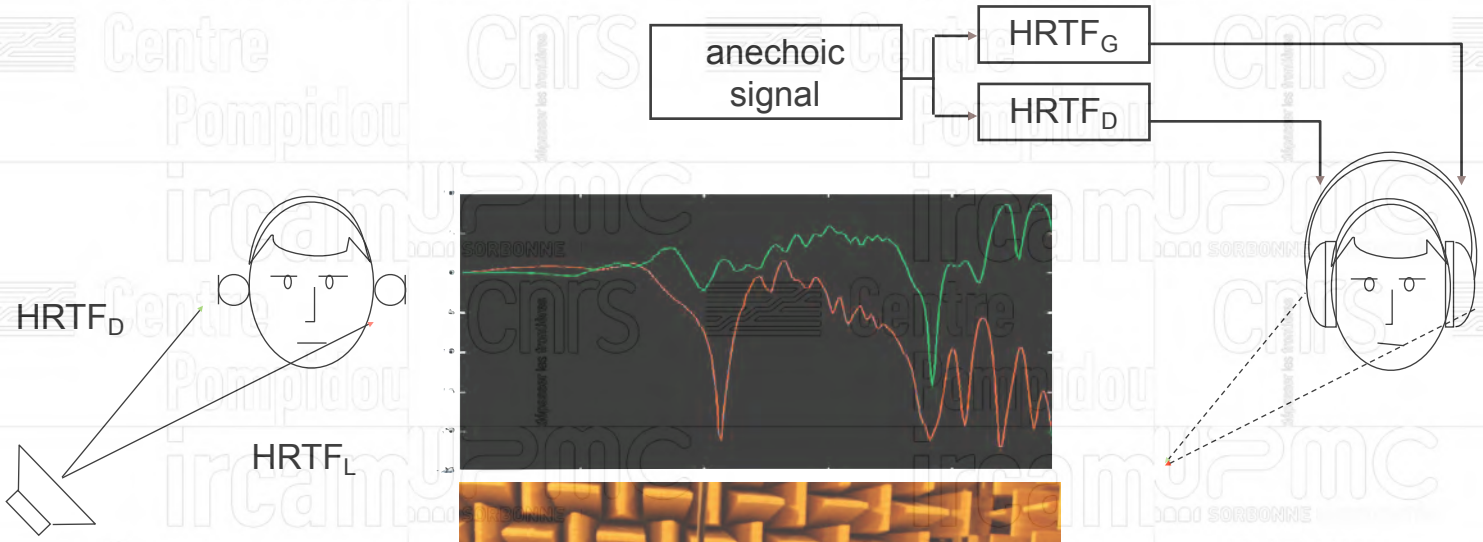
4 - Auditory spatial cognition

5 - Distributed sound spatialization

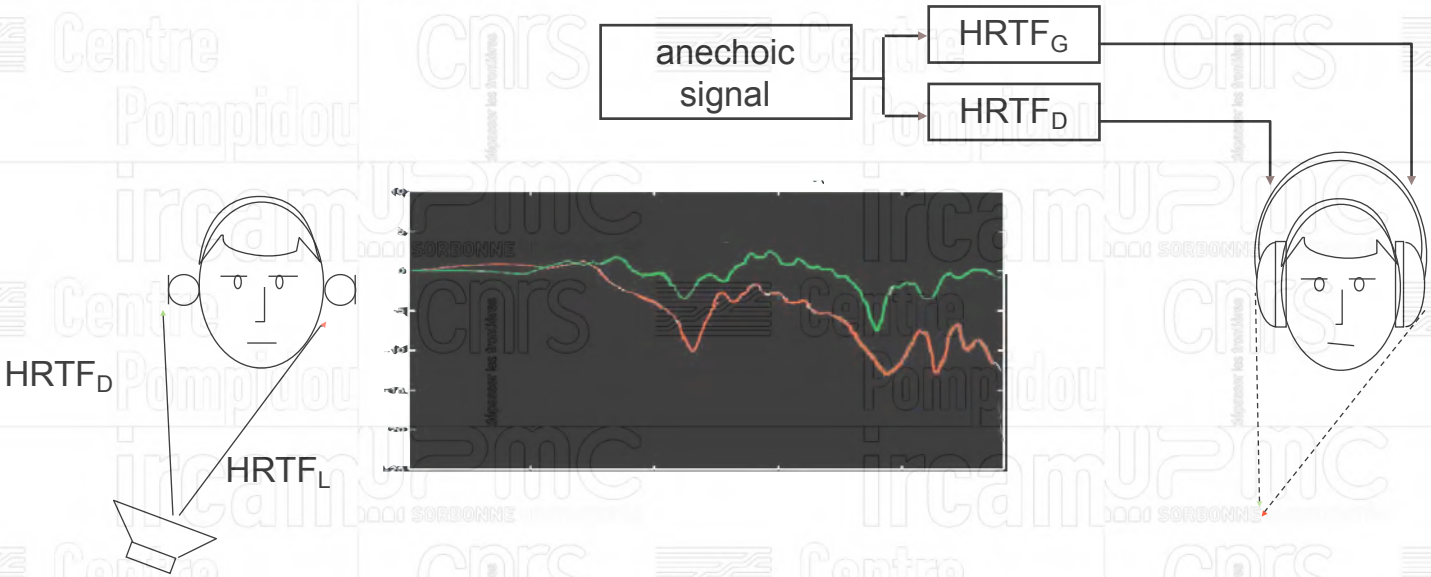
Sound spatialisation techniques



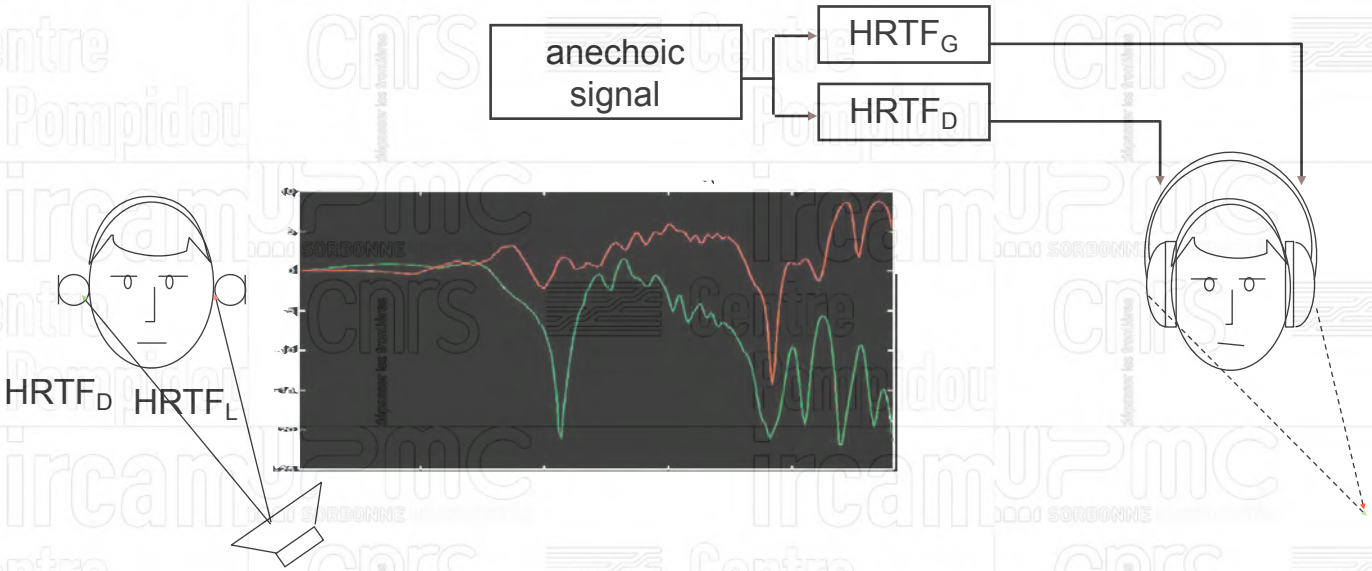
Binaural Synthesis



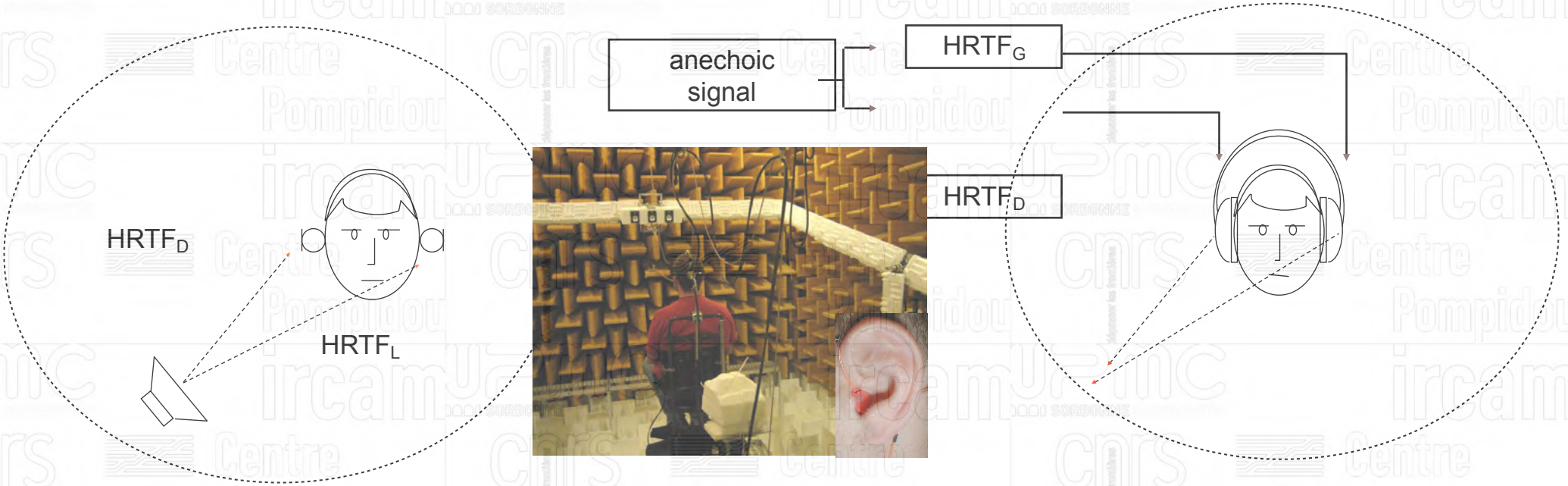
Binaural Synthesis



Binaural Synthesis



Binaural Synthesis



Binaural Synthesis

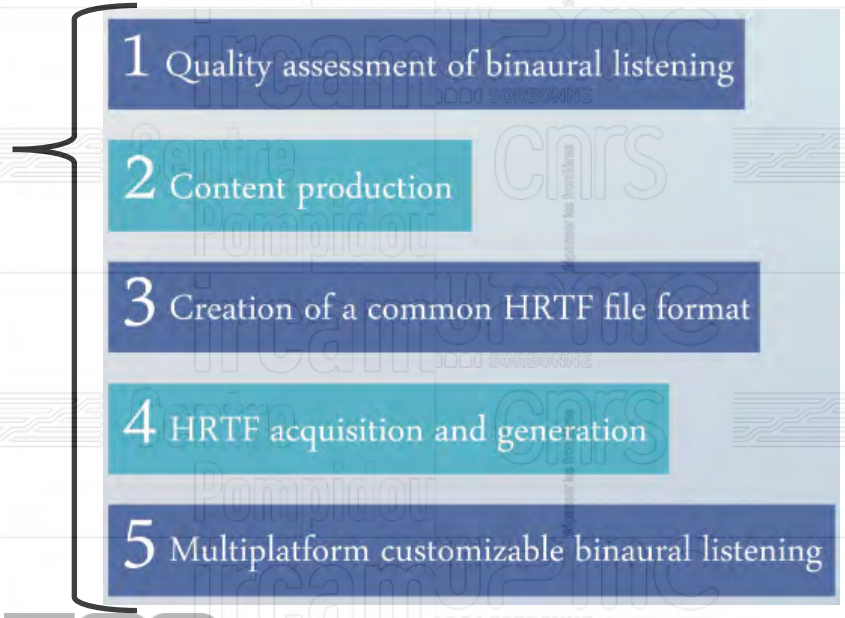
- Scientifique (synthèse & enregistrement)
  - Système de référence pour les études localisation
  - études psychoacoustiques
  - Evaluation perceptive des environnements 3D (e.g. industrie automobile)

- Production Musicale
  - Tête artificielle

- Réalité virtuelle (synthèse)
  - contextes immersifs & interactifs
  - Simulateurs (industrie et recherche)
  - Industrie du jeu
  - etc.

The BiLi project

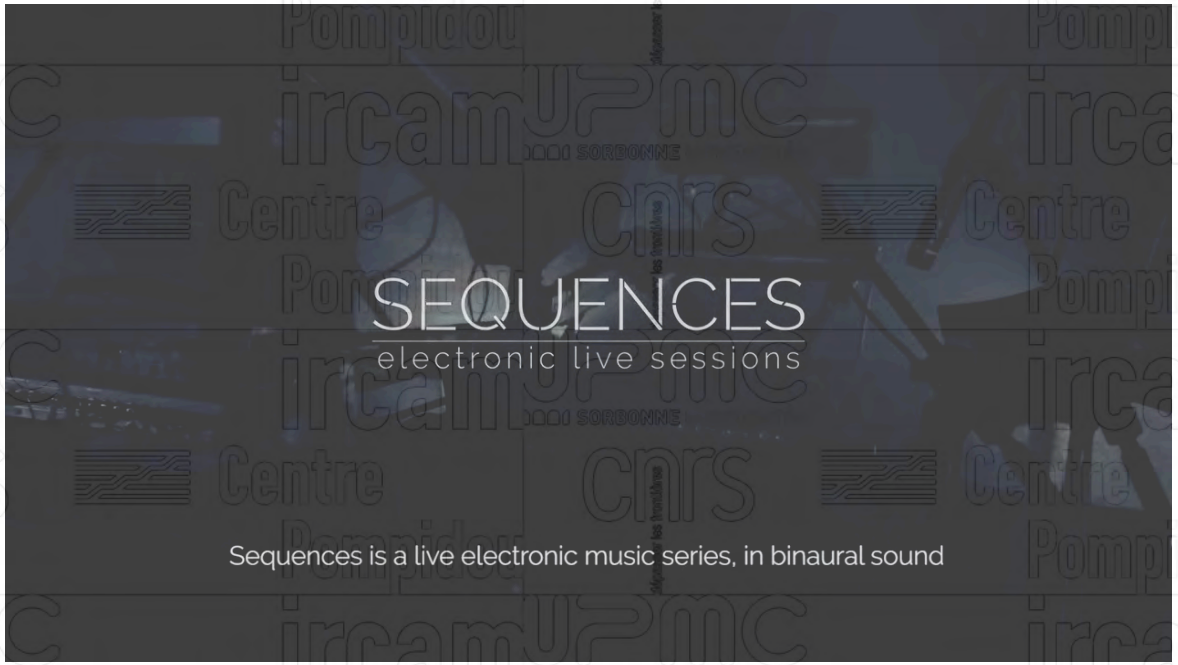
- BiLi project : offer binaural rendering solutions to everyone
- French collaborative project conducted by the 3 major french companies in broadcast and sound communication : France TV, Orange, Radio France



Binaural technology for 3D audio broadcast

RADIO FRANCE

FRANCE TELEVISION



Binaural Broadcast

Binaural technology for 3D audio broadcast

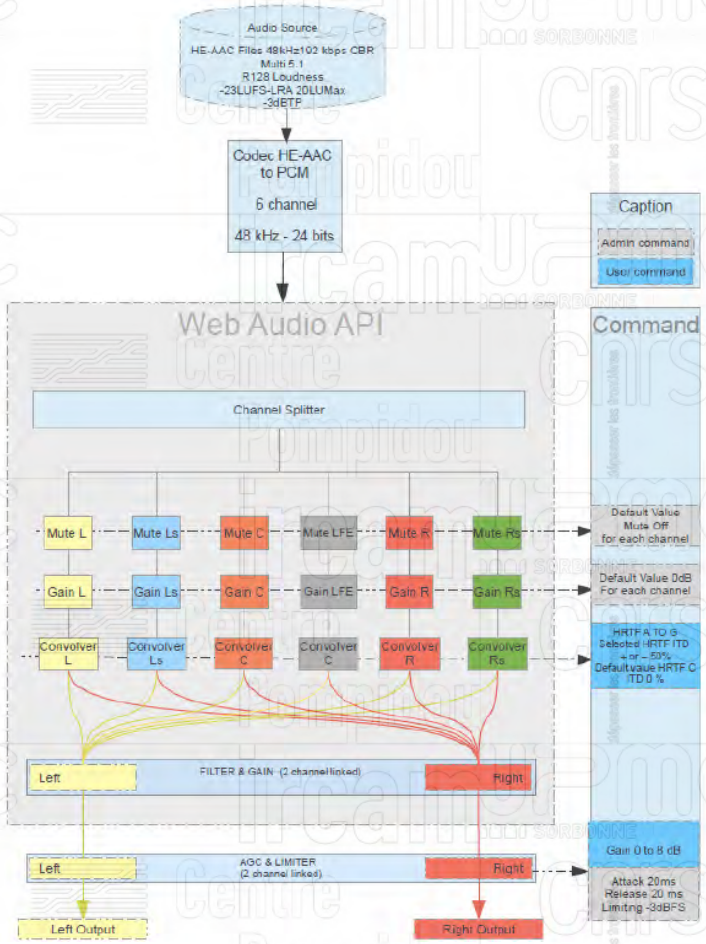
First Version

- 5.1
- binaural (generic HRTFs)
- stereo

Binaural Broadcast

H. Dejardin, E. Roncière « nouvOson website: how a public radio broadcaster makes immersive audio accessible to the general public ».
***57th AES International Conference**: The Future of Audio Entertainment Technology – Cinema, Television and the Internet (March 2015)*

Binaural technology for 3D audio broadcast



2nd Version

- source format 5.1
  - binaural decoder (Web Audio API)
  - 7 HRTFs (A to G)
  - ITD control (+/- 50%)

H. Dejardin, E. Roncière « nouvOson website: how a public radio broadcaster makes immersive audio accessible to the general public ».
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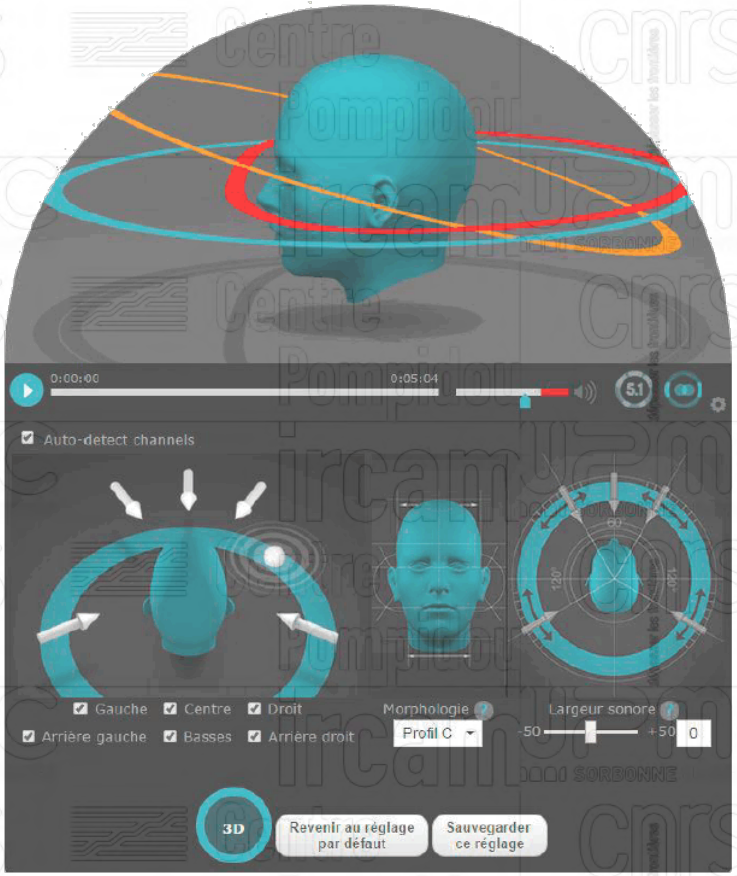
Binaural technology for 3D audio broadcast



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AES69-2015 Spatial acoustic data file format

Objectives

- *R&D Studies : Analysis of HRTFs from various databases*
  - *HRTF classification*
  - *each stored in its own format*

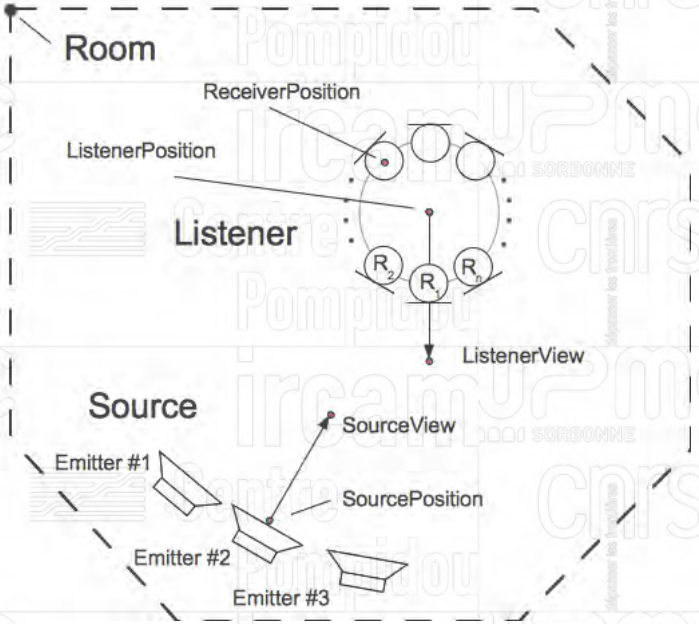
- *Audio applications :*
  - *spatialize sounds with HRTFs originating from arbitrary databases*
  - *binaural applications interchange format*

P. Majdak, Y. Iwaaya, T. Carpentier, M. Noisternig et al., *Spatially Oriented Format for Acoustics A data exchange format representing Head Related Transfer Functions*, **134th AES Convention 2013**

Binaural Broadcast

AES69-2015 Spatial acoustic data file format

Spatially Oriented Format for Acoustics

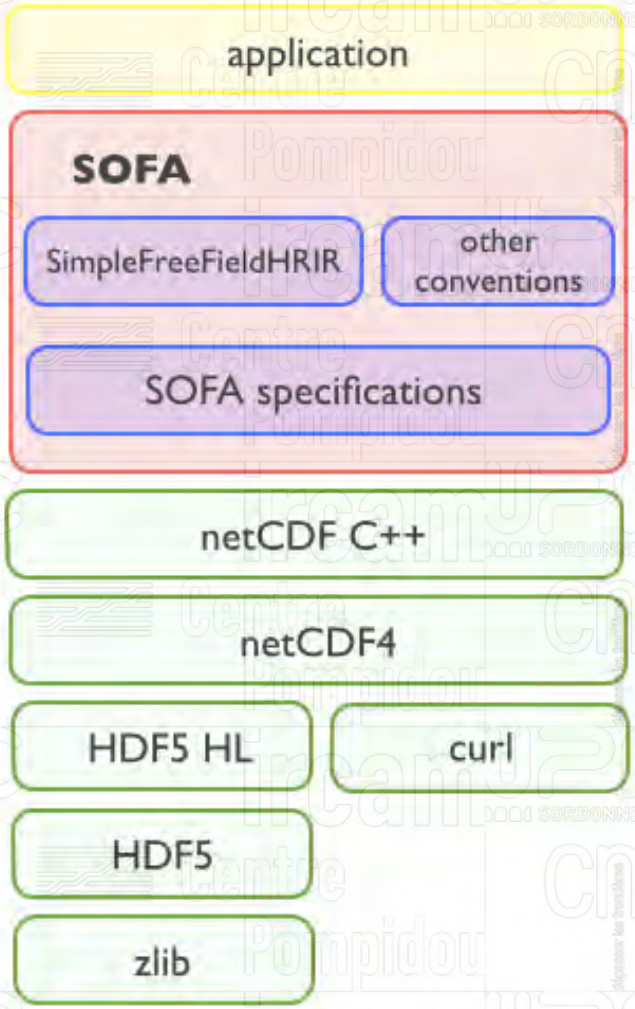


after Majak et al.

P. Majdak, Y. Iwaaya, T. Carpentier, M. Noisternig et al., *Spatially Oriented Format for Acoustics A data exchange format representing Head Related Transfer Functions*, **134th AES Convention 2013**

P. Majdak, H. Ziegelwanger, W. Hagen, M. Noisternig, Efficient Representation of Head Related Transfer Functions using Spatially Oriented Format for Acoustics, **21st ICSV, Beijing July 2014**

AES69-2015 Spatial acoustic data file format



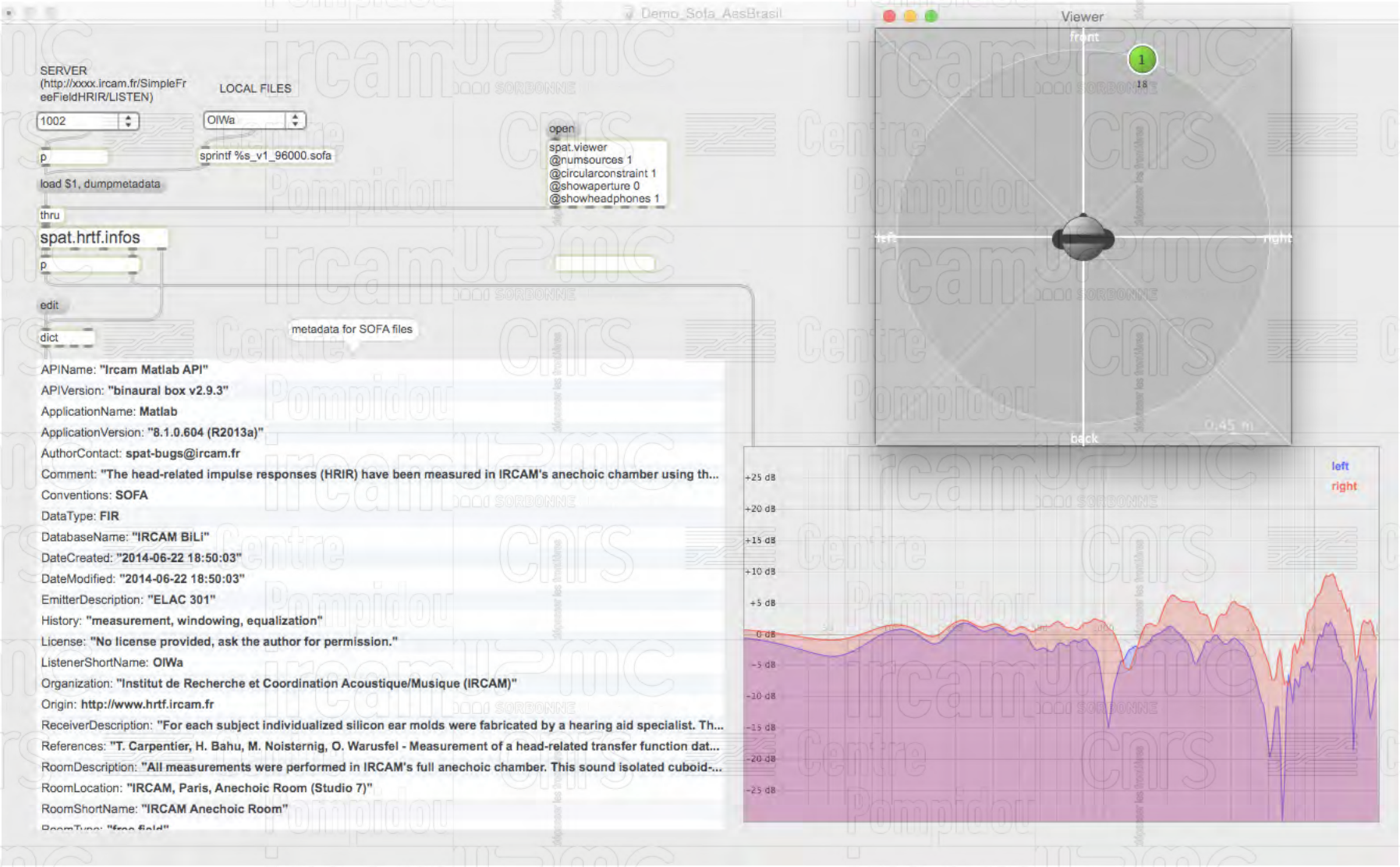
SOFA Implementation

- Numeric Container netCDF
  - Self-described
  - Structured data and multidimensional arrays
  - Explicit naming of dimensions
  - huge file support (> 4G)
  - Partial Data access

  - Machine-independent
  - Network-transparent
  - Compressed

  - Actively developed (University Corporation for Atmospheric Research, UCAR, >100 university

AES69-2015 Spatial acoustic data file format



Binaural Broadcast

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Cognition spatiale auditive

Notre perception/représentation de l'espace résulte d'une combinaison de plusieurs modalités sensorielles encodant chacune l'espace d'une manière spécifique.

Nos facultés de localisation auditives ne se construisent pas indépendamment des autres modalités sensorielles. Elles se construisent à travers des mécanismes d'intégration multisensorielle (vision, proprioception).

crédit: Cnrs Vrignaud

KMB - july-Sept 2003 - 4500 visitors

Influence/résolution de conflits sensoriels (entre modalités ou entre les mondes réels/virtuels).

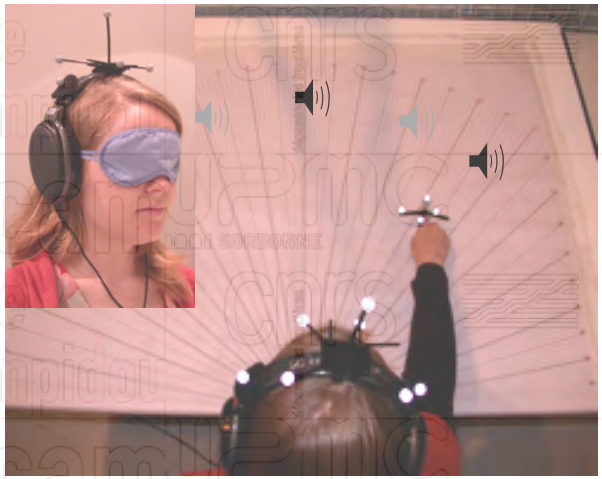
Sense of location

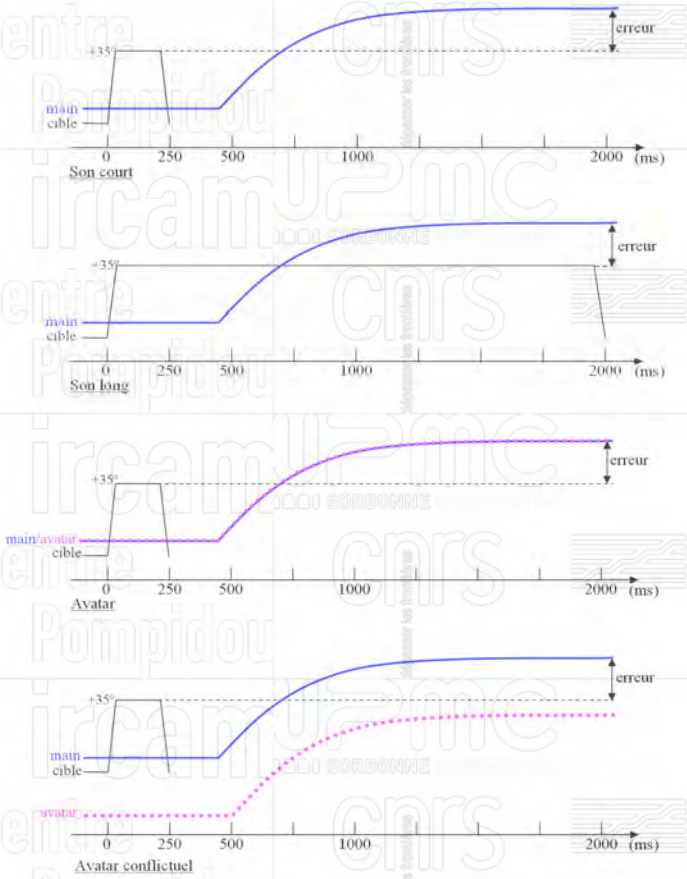
Pour un être complètement immobile il n'y aurait ni espace, ni géométrie, c'est en vain qu'autour de lui les objets extérieurs se déplaceraient.

Quand on dit que nous localisons un objet en tel point de l'espace, cela signifie simplement que nous nous représentons les mouvements qu'il faut faire pour atteindre cet objet (…) nous nous représentons les sensations musculaires qui les accompagnent et qui n'ont aucun caractère générique, qui par conséquent n'impliquent nullement la préexistence de la notion d'espace.

Henri Poincaré in « La valeur de la Science » 1905

coordination auditivo-motrice chez l'Homme : avatar sonore



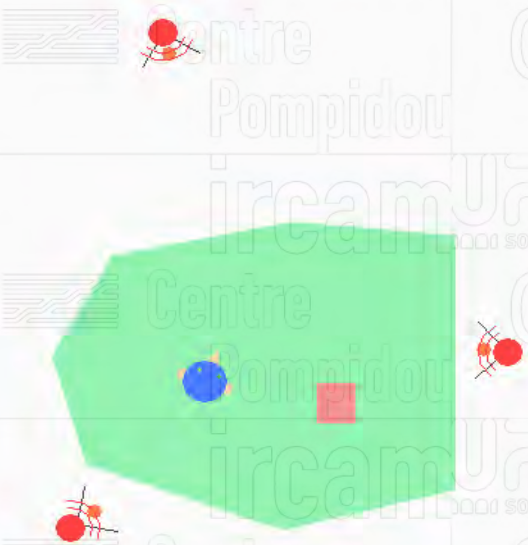


Stimuli :

Les sons (bruit blanc) proviennent de 5 azimuts différents : -35°, -20°, 0°, 20°, 35° (-20° et 20° sont des distracteurs, seules les réponses pour -35°, 0° et 35° sont analysées). Le sujet indique la position du stimulus en pointant l'index droit.

Audition et espace

Le sujet est dans le noir, équipé d'un casque audio sans fil et d'un capteur de position de tête : l'espace auditif virtuel est mis à jour en temps réel d'après les mouvements de la tête.



- Zone de test (en vert) limitée par une frontière auditive (vent)
- Cible auditive "cachée" : sifflet (en rose)
- 3 sources sonores (piano, cigale, voix)

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Distributed Spatialisation

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Distributed soundscape recording

Server

sound scene reconstruction

The signals captured by the different smartphones are collected by a server and processed to build a coherent sound scene according to the selected standpoint.

Distributed Spatialisation

29th May 2015

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UNIVERSIDADE DE SÃO PAULO

FAPESP

ircam UPMC SORBONNE UNIVERSITÉS
Centre Pompidou
cnrs

Distributed speech enhancement

The signals captured by the neighboring smartphones are used to create local speech enhancement.

Zeng, Y. and Hendriks, R.C. (2012), Distributed Delay And Sum Beamformer For Speech Enhancement In Wireless Sensor Networks Via Randomized Gossip, in IEEE Int. Conf. Acoust., Speech, Signal Processing

Mobile phone orchestra

Distributed Spatialisation

29th May 2015

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Distributed sound spatialization (ANR COSIMA Project)

- Collective experiences
- Same physical space
- Heterogenous distributed devices
  - computation
  - interaction
  - sound diffusion
- Based on standard HTML5 & Web Audio API
  - standard web-pages, no application needed
  - on-going standard, but already wide-spread
  - partial support depends on browser & OS

Distributed sound spatialization (ANR COSIMA Project)

COSIMA

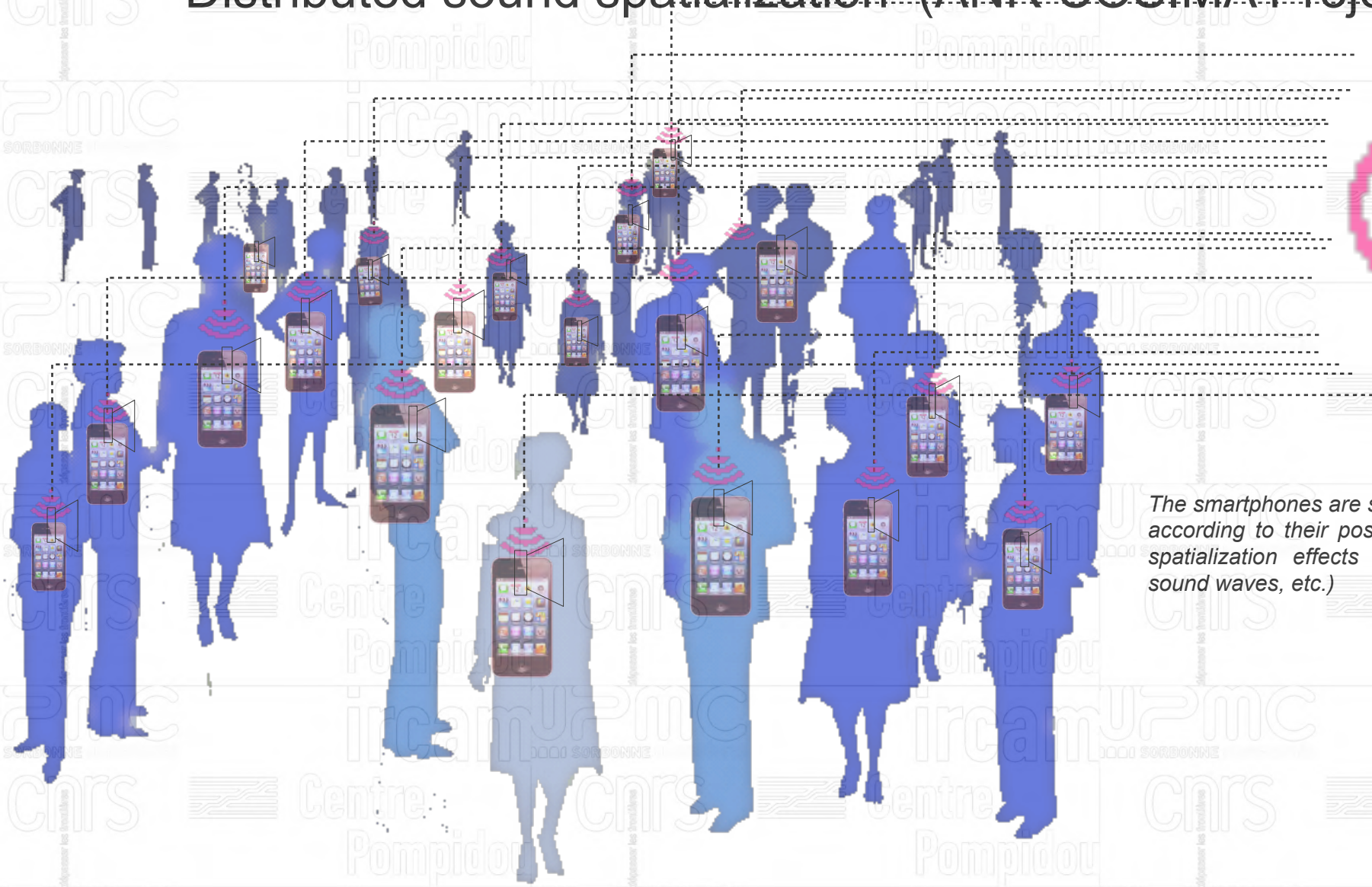
http://cosima.ircam.fr/collective-sound-checks/

Distributed sound spatialization (ANR COSIMA Project)

COSIMA

Norbert schell@ircam.fr
sebastien.Robaszkiewicz@ircam.fr

Distributed sound spatialization (ANR COSIMA Project)



Server

The smartphones are successively triggered, according to their position, to create sound spatialization effects (virtual sound paths, sound waves, etc.)

Distributed Spatialisation

Distributed sound spatialization (ANR COSIMA Project)

Sound events or sound synthesis parameters are propagating between nearby smartphones to create sound spatialization effects.

Distributed Spatialisation

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N. Schnell, V. Saiz, K. Barkati and S. Goldszmidt of Time Engines and Masters : an API for scheduling and Synchronizing the Generatino and Palyback of Event Sequences and Media Streams for the Web Audio API , WAC'15 Paris January 2015

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http://cosima.ircam.fr/collective-sound-checks/

contributions :

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